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6. AUTHOR(S)

John A. Stern
Timothy B. Brown

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Bio-Behavior Analysis Systems, LLC
7472 Woodlawn Colonial Lane
Saint Louis, MO 63119-4441

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
AFOSR/NL Mail Room 3112
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14. ABSTRACT

Military personnel are frequently required to perform tasks for which fatigue is a common problem. Lapses in alertness associated with fatigue are major contributors to human error. We have proposed to create a system that will use unobtrusively obtained bio-behavioral measures to detect such lapses in alertness and thus lower the incidence of human errors. In the current phase of this work, we have developed and used a test task (EPVT) which incorporates the need for visual search activity as well as involves a cognitive component. For non-sleep deprived subjects, this task generates lapses in performance as demonstrated by significant changes in reaction time (RT) as a function of Time-on-Task. We have also discovered a number of bio-behavioral variables for which significant alteration in the variables is associated with long latency responses and thus with lapses in alertness. The most impressive result to-date demonstrates significant differences in pupil diameter associated with stimuli where RT is slow, normal and fast. Significant changes in a number of bio-behavioral measures also occur as a function of ToT. There are individual differences in the occurrence of bio-behavioral signs of impairment in alertness to the task. We are developing prototype software for monitoring operator alertness.

15. SUBJECT TERMS

Alertness, eye activity, heart period, human error, lapses, performance, pupil, vigilance

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a. REPORT	b. ABSTRACT	c. THIS PAGE		44	Timothy B. Brown
					19b. TELEPHONE NUMBER *(include area code)* (314) 494-1108

Bio-Behavior

ANALYSIS SYSTEMS

Detection of Human Fatigue

Written By: John A. Stern & Timothy B. Brown

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REAL-TIME DETECTOR OF HUMAN FATIGUE

Final Technical Report

Detection of Human Fatigue

1 Introduction

Fatigue is a continuing problem for modern humans. Lack of sleep is reported to be the greatest producer of such feelings. Objective, especially physiological indicators of fatigue are being developed, albeit slowly. The most common indicator is impaired performance with reaction time as one of the major measures. As people become fatigued there is a significant increase in the frequency with which longer than "normal" reaction times occur. As fatigue increases there is an increase in the frequency with which such signs occur. It should be pointed out that we are not dealing with a general slowing of responding; rather the frequency of longer than normal response latencies increases. Similarly, the likelihood of not responding to signals increases as a function of time on task.

Since sleep deprivation is an accepted procedure for producing feelings of fatigue, much of the research on human fatigue has focused on the effect of sleep deprivation on alterations in performance. It is well known that measures of performance decrement do not occur, or occur only minimally, when tasks are of short duration as well as when rest periods are allowed between performance of different tasks or segments of the same task. The Psychomotor Vigilance Task (PVT) is one of the few tasks that consistently demonstrates alterations in performance as a function of variables such as sleep deprivation and the ingestion of psychoactive substances. Duration of task performance to demonstrate such effects is usually 10 and in some cases 20 minutes. No studies have been conducted using longer periods of task performance to determine whether performance decrements occur as a function of Time on Task (ToT), in the absence of sleep deprivation or the administration of psychoactive agents.

The development of physiological measures associated with feelings of "fatigue", especially measures that can be applied in operational environments has been slow. To be usable in operational settings, the measurement should not place constraints on the operator. Thus measures requiring the application of sensors have to be avoided. Though electroencephalographic measures have been developed that detect fatigue effects, the use of this technique requires application of electrodes. We have singled out two physiological measures involving remote monitoring technology and one measure involving a behavioral measure that we believe to have a high potential for identifying fatigue effects. These are video based measures of oculomotor activity, Laser-Doppler Vibrometry for the recording of measures such as cardiovascular and muscle activity and third, a behavioral measure, namely instrumenting the mouse to capture slight pressure changes that may indicate anticipation and under some circumstances the phenomenon of "motor overflow".

We developed a task labeled the Enhanced Psychomotor Vigilance Task (EPVT) with the expectation that we would see alterations in alertness as a function of ToT. Because of our interest in using oculomotor measures, we designed our task so that gaze shifts had to be made. We also incorporated a more cognitive requirement by adding a running memory task to the

EPVT. Our first concern was with demonstrating that this task produces ToT effects on response latency and in concurrently recording a number of bio-behavioral measures with the intent of identifying elements associated with performance impairment.

2 Experimental task

The psychomotor vigilance test (PVT) was developed by Wilkinson (1982) and improved by Dinges and collaborators (1991) to evaluate performance lapses. It is sensitive to sleep deprivation as well as pharmacological manipulations. Central nervous system depressants decrease and central nervous stimulants improve performance on this test. We believe that demonstrating attentional lapses in non-sleep deprived and non-pharmacological conditions requires a more sensitive task, one that incorporates perceptual as well as cognitive demands. We developed a task called the enhanced psychomotor performance task (EPVT). We enhanced the task in two dimensions, the first perceptual, the second cognitive in nature. The perceptual manipulation requires subjects to not only attend to centrally presented information (as found in the PVT), but to information presented at 3 locations, a central one and 10 degrees to the left and right of the central location. Subjects cannot predict the location of stimulus presentation. A second manipulation requires subjects to abstract information rapidly. The cognitive manipulation requires subjects to retain information (a running memory task) and respond after a sequence of specific events has transpired.

The EPVT, unlike the PVT, presents the operator with three (rather than one) count-up millisecond timers. Count-up is initiated on one of the three timers, and the subject is required to depress the left mouse button to stop the timer. For the cognitive component, the subject is required to retain information about the nature of the digit in the millisecond position of the timer. She is required to depress the right mouse button following a sequence of three odd integers at the millisecond position. She thus has to abstract information, retain it in memory, and finally respond after a specified sequence of odd integers has been presented. The millisecond segment of the timer is under operator, rather than subject control. We thus control, without the subject's awareness, the frequency with which a sequence of three odd integers occurs. Stimulus onset asynchrony is variable, averaging 2.5 seconds. If a subject does not respond to a stimulus, the next stimulus occurs automatically after an interval of 4.0 sec. The subject's manual response to detecting the scrolling timer stops the timer and the time remains on the screen for 400 ms. The timer then resets to the default value of 0000 at the three locations where stimuli are presented.

3 Data collection procedures

Subjects were Washington University student volunteers and were paid $30.00 for participating in this experiment. They came to an office at the Washington University School of Medicine and were required to fill out a number of forms including informed consent. Following this, they were brought to the laboratory and the instrumentation and procedure were explained. The camera based data acquisition system was calibrated. This took on the average 30 seconds. A piece of reflecting tape was placed over the site from which cardiac activity was to be recorded with the Laser-Doppler Vibrometer (LDV). Subjects then read the instructions for the EPVT and were provided with a 5-minute practice period. The experimenter observed responses to assure

her that the subject was following instructions. Some subjects had difficulty in understanding instructions for the memory task. The practice period gave us the opportunity to further instruct them in the performance of this task. We also monitored reaction time (RT) to the simple reaction time (SRT) task and prior to starting the experiment proper asked subjects to attempt to maintain their response latencies at or better than a specified level. This level was dependent on their response latency during the practice task. The suggested latency was identified as their modal latency plus approximately 50 ms.

We collected usable data for 20 subjects, 10 male, 10 female. Data for 5 subjects was discarded principally because of the unavailability of one of the data sets, camera based data or Laser-Doppler Vibrometry data. Data loss was occasioned in one case by the subject not completing the 60 minutes of task performance, in four cases because of major movement artifact interfering with our ability to record acceptable signals.

4 Measures utilized

The following measures were abstracted from the collected data.

4.1 Simple reaction time – mouse based responses

4.1.1 Time on Task (ToT) effects

4.1.2 Long latency responses – their temporal distribution

4.1.3 Short latency responses – their temporal distribution

4.1.4 Missed signals and interstimulus responses

4.1.5 Comparison of simple reaction time responses using the mouse and pressure sensors

4.2 Running memory task performance

4.2.1 Time on task effects

4.2.2 Accuracy measures

4.3 Camera based measures associated with response latency

4.3.1 Saccadic eye movements to target (tT) and return from target (rT)

4.3.2 Timing of saccadic eye movements with respect to response enactment

4.3.3 Head movements associated with saccades

4.3.4 Pupil diameter measures reflecting performance impairment

4.3.5 Pupil diameter changes associated with "long", "normal" and "short" latency responses

4.3.6 Pupil diameter changes as a function of ToT

4.3.7 Data loss considerations

4.4 Cardiovascular measures

4.4.1 Cardiovascular measures associated with "expectancy"

4.4.2 Fractionation of heart period into; pre-ejection; left ventricular ejection, and post ejection periods.

5 Results obtained

5.1 Simple reaction time – mouse based responses

5.1.1 Time on Task (ToT) effects

Analysis based on mean reaction time

Table 1 presents the average reaction time per subject summarized in 5-minute blocks. Figure 1 presents the average reaction time across 20 subjects.

	m10	m11	m12	m13	m14	m15	m16	m17	m18	m22
0-5	0.344	0.369	0.321	0.527	0.377	0.291	0.359	0.320	0.342	0.412
5-10	0.360	0.403	0.351	0.822	0.352	0.325	0.361	0.320	0.363	0.446
10-15	0.358	0.438	0.353	0.941	0.387	0.312	0.343	0.361	0.378	0.416
15-20	0.350	0.488	0.356	0.799	0.392	0.308	0.375	0.354	0.401	0.410
20-25	0.351	0.512	0.413	0.735	0.368	0.319	0.355	0.475	0.412	0.408
25-30	0.380	0.609	0.390	0.925	0.367	0.353	0.389	0.517	0.464	0.410
30-35	0.387	0.579	0.402	0.504	0.388	0.325	0.435	0.450	0.472	0.425
35-40	0.392	0.500	0.440	0.409	0.403	0.338	0.570	0.574	0.518	0.437
40-45	0.402	0.577	0.481	0.404	0.394	0.359	0.629	0.534	0.663	0.439
45-50	0.417	0.644	0.452	0.422	0.434	0.421	0.644	0.615	0.786	0.480
50-55	0.450	0.616	0.537	0.462	0.419	0.400	0.439	0.576	0.803	0.484
55-60	0.405	0.614	0.513	0.417	0.405	0.354	0.724	0.548	0.899	0.537

	f10	f12	f13	f14	f17	f18	f20	f21	f22	f23
0-5	0.396	0.356	0.357	0.490	0.373	0.300	0.382	0.418	0.439	0.319
5-10	0.366	0.359	0.362	0.833	0.394	0.304	0.369	0.445	0.562	0.324
10-15	0.428	0.358	0.352	1.582	0.408	0.305	0.360	0.485	0.556	0.328
15-20	0.496	0.331	0.363	1.442	0.451	0.314	0.424	0.450	0.638	0.338
20-25	0.525	0.344	0.381	1.127	0.486	0.317	0.415	0.462	0.587	0.346
25-30	0.602	0.351	0.379	0.610	0.457	0.317	0.407	0.468	0.475	0.344
30-35	0.648	0.371	0.411	1.047	0.478	0.314	0.420	0.436	0.409	0.352
35-40	0.612	0.379	0.502	0.928	0.752	0.325	0.421	0.421	0.448	0.349
40-45	0.710	0.371	0.504	1.283	0.576	0.325	0.434	0.428	0.475	0.343
45-50	0.930	0.357	0.461	1.016	0.702	0.320	0.441	0.453	0.466	0.358
50-55	0.749	0.361	0.523	0.832	0.957	0.323	0.499	0.433	0.502	0.362
55-60	0.589	0.372	0.545	0.445	0.787	0.336	0.486	0.435	0.425	0.362

Table 1 - Average reaction time per subject

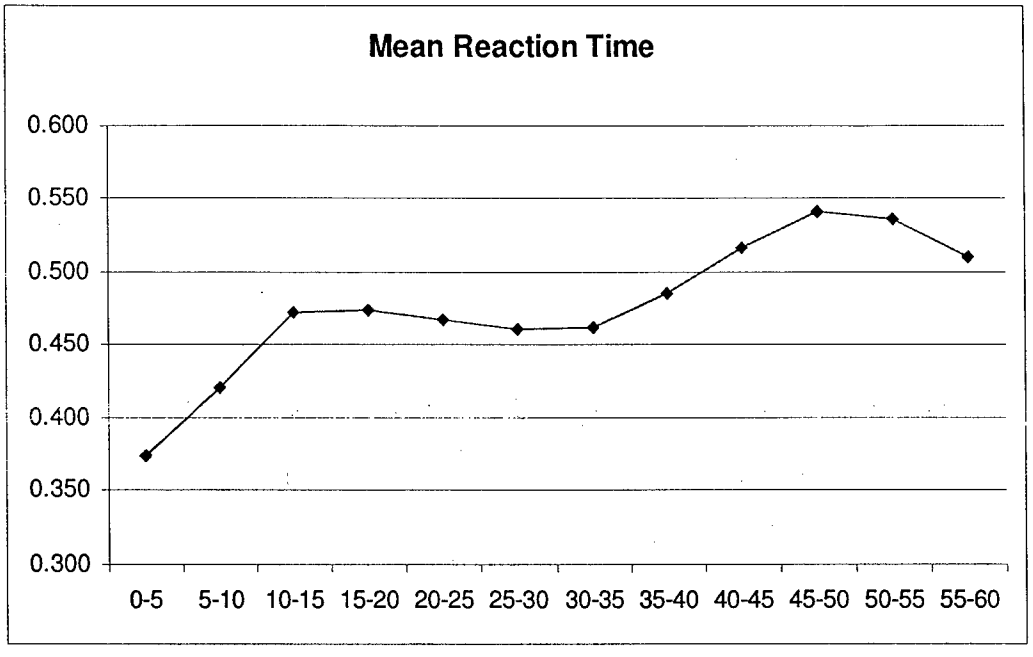


Figure 1 - Average reaction time across subjects

It is readily apparent from Figure 1 that subjects demonstrate an increase in reaction time over the initial 15 minutes of task performance, maintain that level of performance for the next 20 minutes and then demonstrate a further increase in average reaction time.

Analysis based on "normalized" reaction time measures

Because of the large differences between subjects in reaction time, the data was "normalized" by expressing average reaction time for specified periods as a ratio of average reaction time for the initial five minutes of task performance.

We presumed that the first five minutes of task performance would be the period in which they were most highly motivated to perform, assuming that there was no learning involved in task performance. We thus used the initial 5-minute period as the "criterion" period and compared performance for successive periods with the initial 5-minute period. This was done for minutes 5-10 and then in 10-minute segments.

Figure 2 presents the results of this analysis averaged over the 20 subjects.

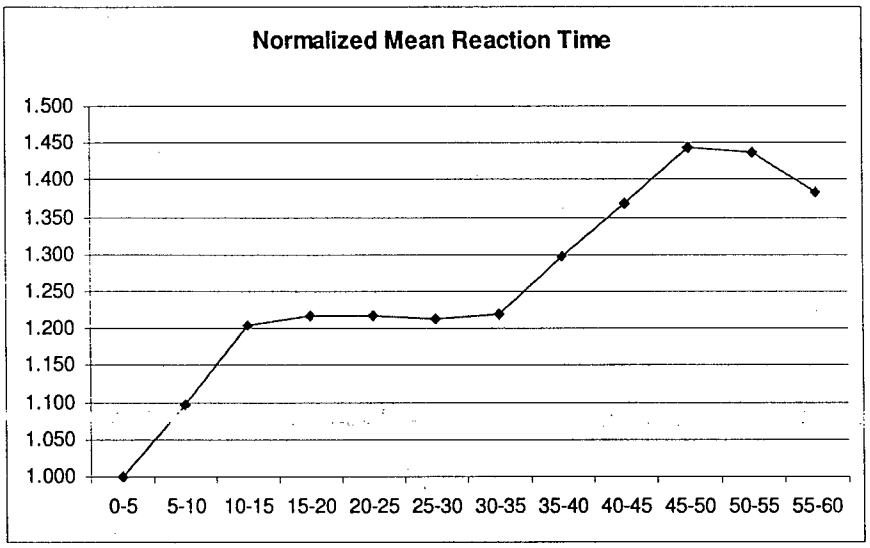


Figure 2 - Normalized reaction time across subjects

It is readily apparent that most subjects had the shortest average RT during the initial 5 minutes of task performance. Three subjects performed better in minutes 5-10 (F10, F20, M14) than the initial 5-minute period and one subject (F12) had her best performance in minutes 10-20 and 20-30. Thus we can conclude that for the majority of subjects, there was little learning involved in performing the simple reaction time component of this task, or that all learning was successfully accomplished in the initial five minute training period.

Were there Time on Task effects? That is, did subjects demonstrate an increase in reaction time as a function of ToT? A number of subjects demonstrated consistent increases in the ratio as a function of ToT. (Under consistent increase we included all subjects who did not show a reversal in the ratio for more than one successive comparison.) This was characteristic of 50% of the subjects, namely F13, F17, F18, F20, F23, M10, M11, M12, M17, and M18.

A number of subjects demonstrated their poorest performance not during the last 10 minutes but during the preceding 10 minutes of task performance. Subjects F10, M14, M15, M16, and M17 fit this description.

There were a number of subjects who did not fit the pattern of increasing reaction time as a function of ToT. Three subjects had their best performance in the last 30 minutes, subjects F21, F22, and M13. Subject F14 showed the least consistent pattern, this is a subject where we could document that she occasionally fell asleep during task performance.

Two subjects had their best performance not during the initial 5-minute period but later in task performance. This characterized subjects F12 and M22. The latter did not demonstrate better performance during these periods but performance equal to that seen during the initial 5 minutes.

In general, we can conclude that most subjects demonstrated an increase in response latency as a function of ToT. Fifteen of the twenty subjects had their longest average reaction times during the last two periods.

On average we see an increase in reaction time from the initial 5-minute period through minutes 10-20, asymptotic performance for the next ten minutes, a second period of increase in reaction time from minutes 30 to 50 and a maintenance at that level for the last 10 minutes. That was the average pattern. We would like to point out that no single subject demonstrated such a pattern.

We also evaluated median reaction time for successive periods as well as normalized median reaction times. Results of these analyses are shown in Figure 3. These results deviate somewhat from the analysis based on means. In all cases the average based on means is longer than that based on medians. That difference increases as a function of time on task. It is our assumption that these differences can be accounted for, in great part, by the significant increase in long latency responses over time. These long latency responses have a greater effect on mean than on median values.

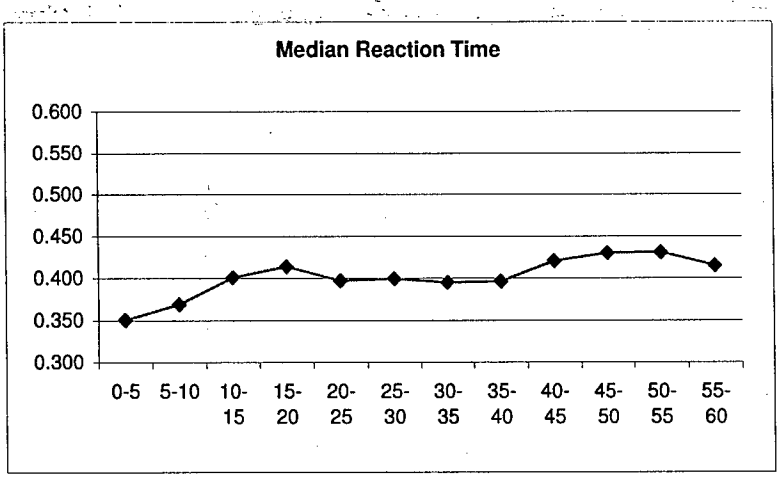


Figure 3 - Median reaction time across subjects

5.1.2 Long latency responses – their temporal distribution

Since our major concern is with the identification of lapses in alertness and since we hypothesized that there should be an increase in long latency responses as a function of ToT, we performed the following analysis.

We identified the 50 longest latency simple reaction time (SRT) responses made by all 20 subjects assuming that long latency responses are most likely associated with brief periods of loss of alertness. If such periods increase in frequency as a function of time on task, the distribution of these 50 events should show an increase in frequency of occurrence over time. The frequency of occurrence of these events in consecutive 10-minute periods is depicted in Table 2 and Figure 4.

Time (seconds)	M10	M11	M12	M13	M14	M15	M16	M17	M18	M22
0-600	2	0	2	11	5	5	0	0	0	4
600-1200	2	3	2	22	8	1	3	1	0	2
1200-1800	6	9	5	13	5	4	2	9	1	2
1800-2400	10	8	9	3	8	6	7	10	0	7
2400-3000	18	16	20	0	10	20	18	16	20	15
3000-3600	13	14	12	1	14	14	20	14	29	20

Time (seconds)	F10	F12	F13	F14	F17	F18	F20	F21	F22	F23
0-600	0	4	0	4	0	12	3	6	8	1
600-1200	0	5	2	19	1	6	7	13	17	3
1200-1800	3	3	3	6	3	8	7	9	10	9
1800-2400	10	14	11	7	11	4	8	6	3	9
2400-3000	21	8	15	10	11	12	5	9	5	13
3000-3600	16	16	19	4	24	14	20	7	7	15

Table 2 - Distribution of long latency responses per subject

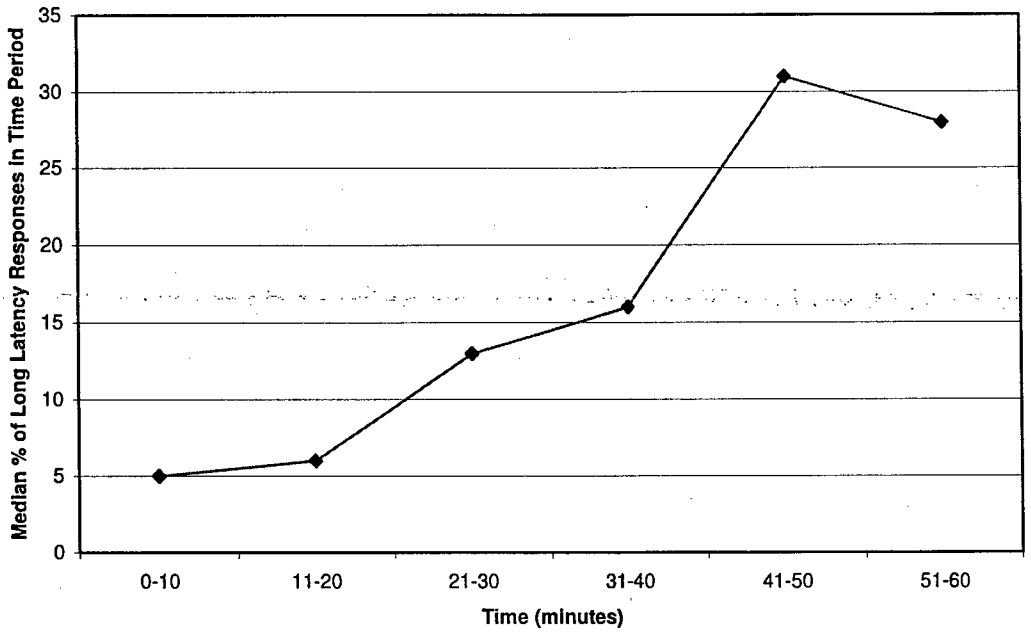


Figure 4- Distribution of long latency responses as a function of ToT

Table 3 shows the mean and median distribution of long latency responses as a percentage of long latency events that occur in successive 10-minute periods.

Time period (seconds)	mean	median
0-600	6.1	5.0
601-1200	11.7	6.0
1201-1800	11.7	13.0
1801-2400	14.6	16.0
2401-3000	26.2	30.6
3001-3600	29.3	28.0

Table 3- Distribution of mean and median long latency responses

A Friedman two-way analysis of variance was performed. The Chi squared r value was 10.0 and significantly different from chance at the $p < 0.005$ level indicating that the highest frequency of long latency events occurred in the last two time periods.

We should point out that the pattern of increasing number of long duration responses as a function of ToT does not characterize every one of the 20 subjects. Four subjects deviate considerably from this pattern (F14, F21, F22, and M13). F14 has been previously described as the subject who demonstrated the largest number and durations of periods of non-responding, from which we inferred that she had dozed off during these "lapses in performance". F21 and F22 demonstrate no consistent change in average reaction time across the successive 5-minute periods. M13 had the slowest reaction times of all subjects (excepting F14) for the initial 30 minutes of task performance, showed a marked drop in reaction time in the next interval, and maintained the faster reaction times for the remainder of the hour.

The distribution of response latencies for 16 of the 20 subjects accords with our expectation that the majority of long latency responses occur late in task performance. All four subjects not demonstrating this pattern (M13, F14, F21, F34) show a pattern of longer latency responses early in task performance. We conclude that for a majority of subjects, there is an increase in long latency responses as a function of ToT demonstrating that the EPVT is sensitive to ToT effects.

5.1.3 Short latency responses – their temporal distribution

Table 4 depicts the distribution of the 50 fastest reaction time responses. We expected that this distribution would be little affected by ToT considerations. As the table demonstrates, there is a decrease in such responses as a function of ToT. The largest number occur during the initial 5-minute period, dispelling the idea that there might be a learning effect. Whatever learning occurred transpired during the practice period for most of our subjects.

EPVT Distribution of 50 Fastest

	F10	F12	F13	F14	F17	F18	F20	F21	F22	F23
1. 600(0-10)	34	2	10	19	20	19	19	9	7	16
2. 1200(10-20)	7	11	15	0	9	8	10	5	4	10
3. 1800(20-30)	2	10	13	7	6	7	10	5	6	7
4. 2400(20-30)	1	3	7	2	6	4	5	10	17	6
5. 3000(30-40)	1	8	4	3	4	4	6	12	10	8
6. 3600(40-50)	5	16	1	19	5	8	0	9	6	3

	M10	M11	M12	M13	M14	M15	M16	M17	M18	M22
1. 600(0-10)	16	16	14	0	10	14	6	24	26	3
2. 1200(10-20)	15	7	11	0	5	15	16	16	15	7
3. 1800(20-30)	6	5	13	2	8	5	13	2	6	8
4. 2400(20-30)	5	9	8	18	13	9	0	4	2	6
5. 3000(30-40)	7	4	1	16	6	6	11	2	1	14
6. 3600(40-50)	1	9	3	14	8	1	4	2	0	12

Table 4 - Distribution of 50 fastest responses

5.1.4 Missed signals and interstimulus responses.

Missed signals are the ultimate in defining periods of loss of alertness. False alarms could be divided into two types. The first involved the enactment of a second response shortly after the response that stopped the timer. Relatively few such responses were obtained. The majority of interstimulus responses could be characterized as "anticipatory" responses. We defined as anticipatory any response that occurred in the second half of the interstimulus interval.

Table 5 depicts the occurrence of such responses grouped in 5-minute intervals. Included in this analysis are both anticipatory responses as well as missed events. The FA:M ratios in the table reflect the number of events that are False Alarms as well as Missed stimuli (no response). Twelve subjects had five or fewer missed events over the 60-minute period; five subjects had between 6 and 10 missed events; two subjects had between 11 and 20 missed events; and one subject had more than 21 such events. The subject with the largest number of such events was F14. Once again, this is the subject who demonstrated obvious periods where her eyes were closed and she appeared to be asleep. She contributed 52% of all the missed signals. Taking missed signals for that subject out of the picture, there are three others who have a relatively high rate of missed signals, subjects F17, M16, and M17. The three in combination contributed 63% of the remaining missed signals. Since these 4 subjects were, in many respects, quite deviant from the remaining 16, we also calculated SRT accuracy for the 16 (more homogeneous) remaining subjects There is a marginally significant ToT effect for the 10 minute averaged data including all 20 subjects $F(5,114)$ 1.902, $p<0.099$. The results of performing the same analysis for the 16 more homogeneous subjects are as shown in Table 6.

Total Mistakes In the Simple Reaction Time Task Across Time (data with mouse only)

	F10(20)	F12(19)	F13(18)	F14(25)	F17(19)	F18(23)	F20(22)	F21(18)	F22(23)	F23(21)
300	0	0	0	1	0	0	0	0	3	1
600	0	0	0	0	1	3	0	0	3	0
900	0	0	0	3	1	1	0	1	1	0
1200	2	2	1	26	2	0	1	0	2	0
1500	2	1	0	21	2	2	2	0	9	0
1800	1	0	2	1	0	3	0	1	5	0
2100	1	1	0	9	3	0	0	4	8	2
2400	0	1	1	3	4	1	1	1	4	0
2700	6	0	0	17	2	1	1	1	6	1
3000	2	1	0	11	3	0	0	0	4	0
3300	4	1	1	5	3	2	0	0	10	1
More	2	0	0	0	7	3	1	0	5	1
Total	20	7	5	97	28	16	6	8	60	6
FA:M Ratio	18:2	7:0	5:0	4:93	18:10	13:3	6:0	7:1	54:6	6:0

	M10(22)	M11(20)	M12(22)	M13(22)	M14(22)	M15(20)	M16(21)	M17(23)	M18(21)	M22(25)
300	2	0	2	0	1	6	1	5	0	3
600	1	5	1	6	3	1	0	1	0	0
900	1	0	4	2	8	0	1	18	0	1
1200	0	1	4	2	3	4	0	7	1	1
1500	0	0	2	4	6	6	13	5	2	4
1800	1	3	1	1	6	2	3	8	0	2
2100	0	1	3	8	10	1	6	7	1	9
2400	1	0	4	7	12	3	6	14	1	1
2700	4	6	0	3	15	3	5	16	0	6
3000	2	2	2	3	8	5	5	9	1	3
3300	6	2	3	5	14	12	5	8	0	6
More	2	4	2	4	6	7	4	20	4	5
Total	20	24	28	45	92	50	49	118	10	41
FA:M Ratio	19:1	18:6	27:1	38:7	83:9	45:5	38:11	102:16	8:2	36:5

Table 5 - SRT accuracy in 5-minute intervals

Time period	Average frequency (N=20)	Average frequency (N=16)
0–600	2.5	2.56
601–1200	5.05	2.69
1201–1800	6.05	4.25
1801–2400	6.97	5.44
2401–3000	7.70	5.38
3001–3600	8.25	7.06

Table 6 - Average frequency of missed signals

5.1.5 Comparison of simple reaction time responses using the mouse and pressure sensors

This analysis was conducted on the subset of subjects (N=5) for which most of each subject's pressure responses could be recorded.

Mouse-Pressure Response Time Differences					
	M10	M11	M13	F11	F12
Mean	0.064	0.055	0.058	0.059	0.064
Standard Error	0.002	0.005	0.004	0.004	0.003
Median	0.064	0.059	0.061	0.058	0.062
Mode	0.064	0.069	0.061	0.061	0.059
Standard Deviation	0.012	0.021	0.018	0.021	0.013
Sample Variance	0.000	0.000	0.000	0.000	0.000
Kurtosis	-0.513	0.855	1.253	2.167	1.651
Skewness	0.162	-0.820	0.790	0.822	1.048
Range	0.045	0.085	0.077	0.101	0.055
Minimum	0.044	0.007	0.033	0.020	0.047
Maximum	0.089	0.093	0.110	0.121	0.101
Sum	1.729	1.109	1.450	1.475	1.605
Count	27.000	20.000	25.000	25.000	25.000
Confidence Level (95.0%)	0.005	0.010	0.007	0.009	0.005

Table 7 - Mouse-pressure response - Time differences

As shown in Table 7, the average time difference between reaction time as measured with the mouse and as measured with the pressure sensor for the five subjects was 60 ms. In all cases the pressure response preceded the mouse identified response. Thus the mouse is neither an accurate nor a reliable tool for measuring time intervals. A number of research papers have demonstrated similar results, the discrepancy varying as a function of the mouse used. When subjects were interviewed after task performance, they occasionally commented on the fact that they had to press the mouse switch a second time to stop the timer. This observation was born out by the finding that one could occasionally see a double response output from the pressure sensor while the mouse output occurred concurrent with the second pressure sensor response.

Though "anticipatory" responses were occasionally obtained with the mouse switch, and an "anticipatory response is defined as one occurring in the second half of the intertrial interval, such responses were much more frequently seen from the pressure sensor. In addition the pressure sensor picked up partial pressure on the mouse prior to the enactment of a response. Whether this response was produced simply by the weight of the finger on the sensor or whether some pressure was exerted could not be determined. Future studies will attempt to improve on the current sensor configuration so that we will get more reliable pressure sensing as well as calibrating the sensor so that one can determine whether partial pressure was exerted. We can say that for four of the five subjects, reaction time was faster when the finger rested on the mouse (reflected in an output from the pressure sensor) than when there was no output from the pressure sensor. Observing subjects performing the task, one could identify times when the finger was on

and other times when the finger was off the sensor. Systematic observations will have to be made to verify the above "impression".

We thus believe that improving the output from the pressure sensors will add an important dimension to not only the accurate measurement of reaction time, but will also allow us to more sensitively monitor "multiple responses", anticipatory responses, and partial as well as "overflow" responses.

Below are a few examples of responses captured with both pressure sensor and mouse that reflect the additional information than can potentially be gathered from a refined analysis of reaction time data.

The following three figures, Figure 5, Figure 6, and Figure 7 are not random samples but were selected to demonstrate some of the measures that can be obtained in addition to RT and response duration.

Data was sampled at 17 millisecond intervals and depicted are 1000 consecutive data points or 17 seconds of data. The channels are identified, the top three deal with output from the pressure sensors located on the left and right mouse buttons, and the channel labeled Pressure Sensor Side samples pressure from the left side of the mouse, the usual location for the right thumb. The next two channels depict the output from the mouse, identifying both onset of response as well as response termination. The mouse left channel reflects simple RT and the mouse right channel shows responses to the running memory task (requiring a response to a sequence of three odd integers). The last two channels depict stimulus information. Stimulus left represents stimuli located to the left of center, stimulus right, to the right of center, and when both stimulus left and right are activated stimulus information is available at the central location. In addition to providing information about stimulus location, these two channels also provide information concerning whether a given stimulus ends in an odd or an even integer. If the stimulus bar is narrow, it identifies an even integer, wide, an odd integer.

Figure 5 shows information sampled between 274 and 291 seconds following the initiation of the experiment. Our focus here is on the left pressure sensor response. To the first stimulus (right) we see concurrent responses from both the mouse and pressure sensor. Then there is a pressure sensor response not reflected in mouse activation. The next stimulus, also at the right side of the display, demonstrates anticipatory activity from the pressure sensor channel. The next stimulus, at the central location, demonstrates the non-linearity of the current sensor output. Partial pressure is exerted on the mouse and we get only a small "blip" from the pressure sensor concurrent with the mouse response. The same phenomenon is observable in the last two stimuli.

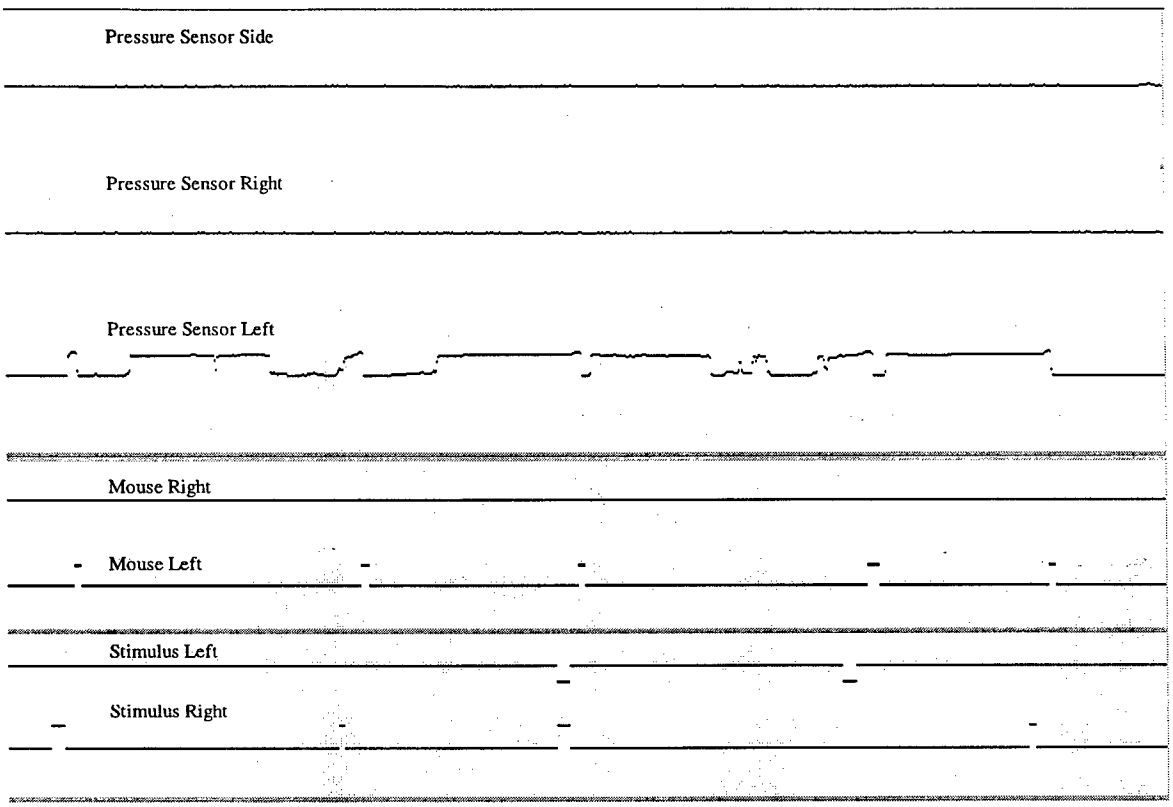


Figure 5 – Data traces for subject F12, 17 seconds starting at time 274 seconds

Figure 6, sampled between 3186 and 3203 seconds following initiation of the experiment, demonstrates examples of what we consider to be "overflow" movements. Note responses on all three pressure sensors. Following the first stimulus shown (central location), there is a concurrent response with mouse and pressure sensor and a concurrent release of pressure on the right sensor. To the second stimulus (on the left), we see concurrent release of both the left and right pressure sensor at response termination. The same is seen on the next trial (central). The minor pressure sensor changes on the side sensor, with perhaps the exception of the response to the last stimulus, do not appear to be time locked to other responses.

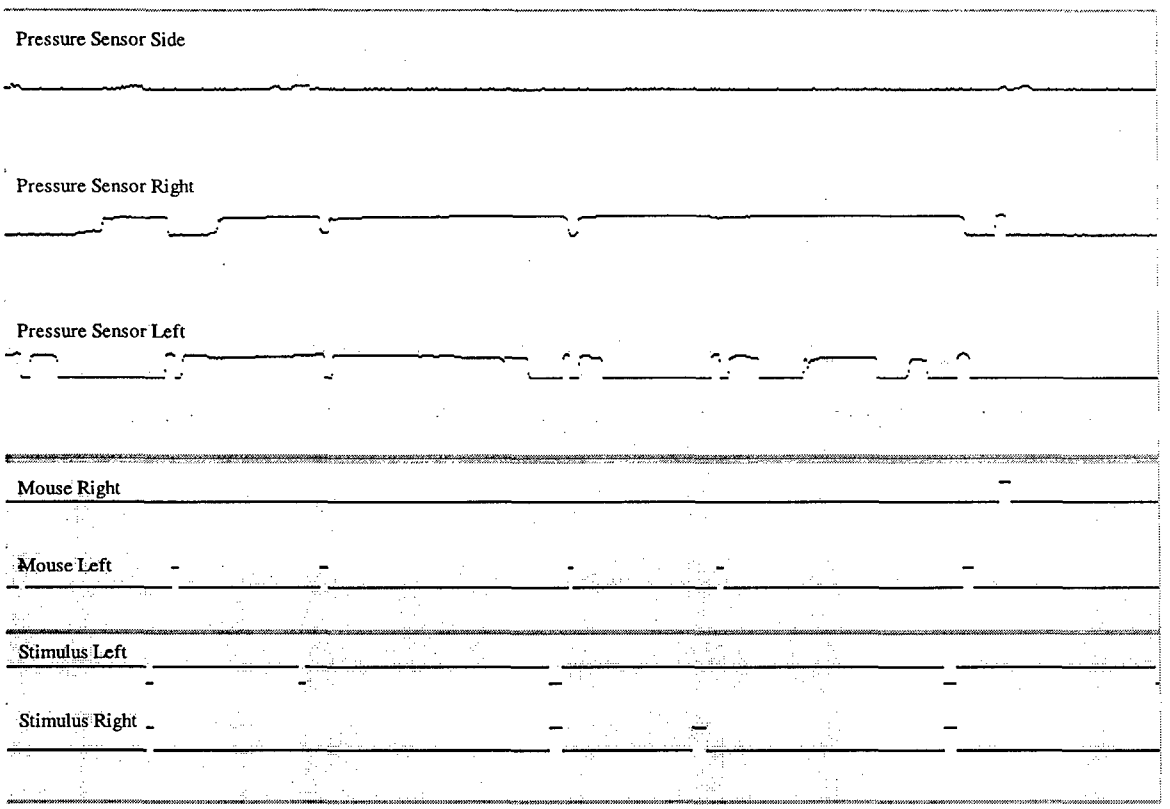


Figure 6 – Data traces for subject F12, 17 seconds starting at time 3186 seconds

Figure 7 demonstrates time locked responses from the left pressure sensor and the side pressure sensor. As the subject depresses the left mouse button, he exerts pressure on the side of the mouse as well. The last stimulus on this figure demonstrates an anticipatory response in both the mouse and pressure channels.

These figures are presented to demonstrate the advantages associated with using pressure sensing as an additional input. We have identified a number of problems with our current procedure for sensing pressure exerted on the mouse and hope to be able to deal with these problems in the phase II effort.

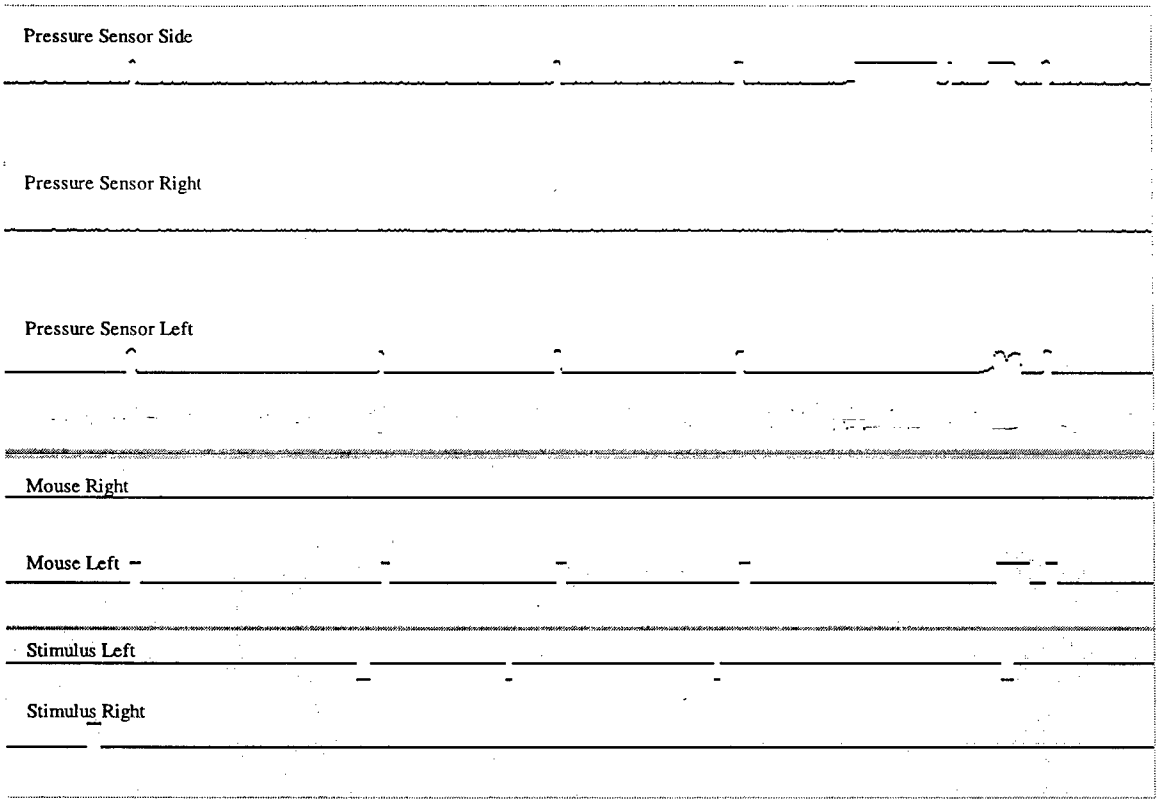


Figure 7 – Data traces for subject M13, 17 seconds starting at time 3232

5.2 Running memory task performance

In the memory component of the EPVT subjects could:

a. Respond accurately
b. Miss a response
c. Enact a false alarm response

Average reaction time was measured from initiation of the simple reaction time response as was also true of false alarm responses. The average reaction time for accurate responses was 0.709 seconds, while that for false alarms was 1.221 seconds. These differences are significant at the 0.0001 level (df 1,728, F=177.35). Thus, most false alarm responses required more time for their enactment, suggesting that there was more uncertainty about the enactment of such responses than was true of correct responses. There was no time on task effect for either response latency or frequency of occurrence for either correct or false alarm responses. These effects mirror those generally seen in performance changes associated with sleep deprivation. The major effect appears to be on simple RT with no or minimal effect on more cognitively loaded variables.

5.3 Camera based measures associated with response latency

5.3.1 Saccadic eye movements to target (tT) and return from target (rT)

Subjects make saccadic eye movements to shift gaze to the target location (tT) and return from the target location to the central or other location (rT). We were surprised by the frequency of occurrence of saccades during the interstimulus interval and suspect that it is the latter saccades that are most sensitive to ToT effects.

5.3.2 Timing of saccadic eye movements with respect to response enactment

To target (tT) saccades generally occur in close proximity to the manual simple reaction time response. We plan to investigate if saccade onset and response onset become more variable as a function of ToT. If the tT saccade follows the manual response by more than 300-400 milliseconds, the subject will not see the numerical information since the RT information is presented for 400 ms following response initiation. Subjects change strategy for acquiring new information. Sometimes there is a series of events where there is no rT gaze shift. The subject waits until the next stimulus occurs before shifting gaze. On 33% of the trials, the subject does not have to change gaze location. We also observed subjects whose gaze shift to stimulus initiation was in the wrong direction. Whether more of these occur as a function of ToT will need to be investigated. We suspect that this may also work in situations where we are not in control of stimulus location. We find that fixation duration, when gaze shift is in the wrong direction, is too short for the acquisition of information from the fixated site. Thus unusually short (as well as unusually long) fixation pauses may index a period of lowered alertness.

Average saccade velocity of tT saccades generally does not change appreciably as a function of ToT; rT saccades are more likely to have occasions when they are slower than normal.

Interstimulus saccades are more likely to be of longer than normal duration. One can occasionally observe slow eye movements (SEM), though in most subjects these only occur after the eyes have closed. They may thus not be useful in the evaluation of alertness. Others have noted that when SEMs occur, it is too late to avoid an accident.

The frequency, as well as amplitude and direction, of interstimulus saccades deserves investigation. One class of such events involves the occurrence of a gaze shift to a new location, a brief fixation pause, and a return to the previous position. We refer to these as "square wave jerks", they are similar to such "jerks" seen as subjects track a target and either lag behind or get too far away from the target location. More such "jerks" are seen in patients suffering from schizophrenia, and a common interpretation is that they are associated with brief periods of interruption of attention to the task of pursuing the target with the eyes.

We have included two figures depicting some of the measures of interest. Figure 8 depicts both horizontal eye movements and minor head movements (inferred from measuring changes in position of the center of the eyeball). The head movements of interest are small. The first stimulus was presented to the right, and we see an eye movement to the right (upward movement in channel 1). The return movement is lost because it coincides with camera data loss occasioned by an eye blink. This figure thus nicely demonstrates that blinks are unlikely to occur as gaze shifts to a target location (tT saccade) and are most likely to occur concurrent with gaze returning

to a central location in anticipation of the next stimulus. Notice also that there is a blink at approximately the same latency from stimulus onset for the third stimulus presented at the central location. No eye movement was required to detect this event. Notice also that the second, third and fourth stimuli end in odd integers requiring a response to the running memory task. The subject successfully makes this response, blinks during the response with a second blink shortly thereafter.

Figure 9 depicts a very different pattern of eye movements than that seen in the previous figure. This person is an active explorer of his environment. The first stimulus is at the central location, and we see an eye gaze shift to the left, rapid return to center before response enactment. The next stimulus is to the right, and the subject shifts gaze to that location from the center. The blink is not concurrent with an eye movement and the eye movement returning gaze to the central location appears to be slower than the move to the target location. Again we see a gaze shift to the right preceding stimulus presentation. The fourth stimulus presentation occurs during a period of data loss, most likely a blink, and is followed by a long latency response.

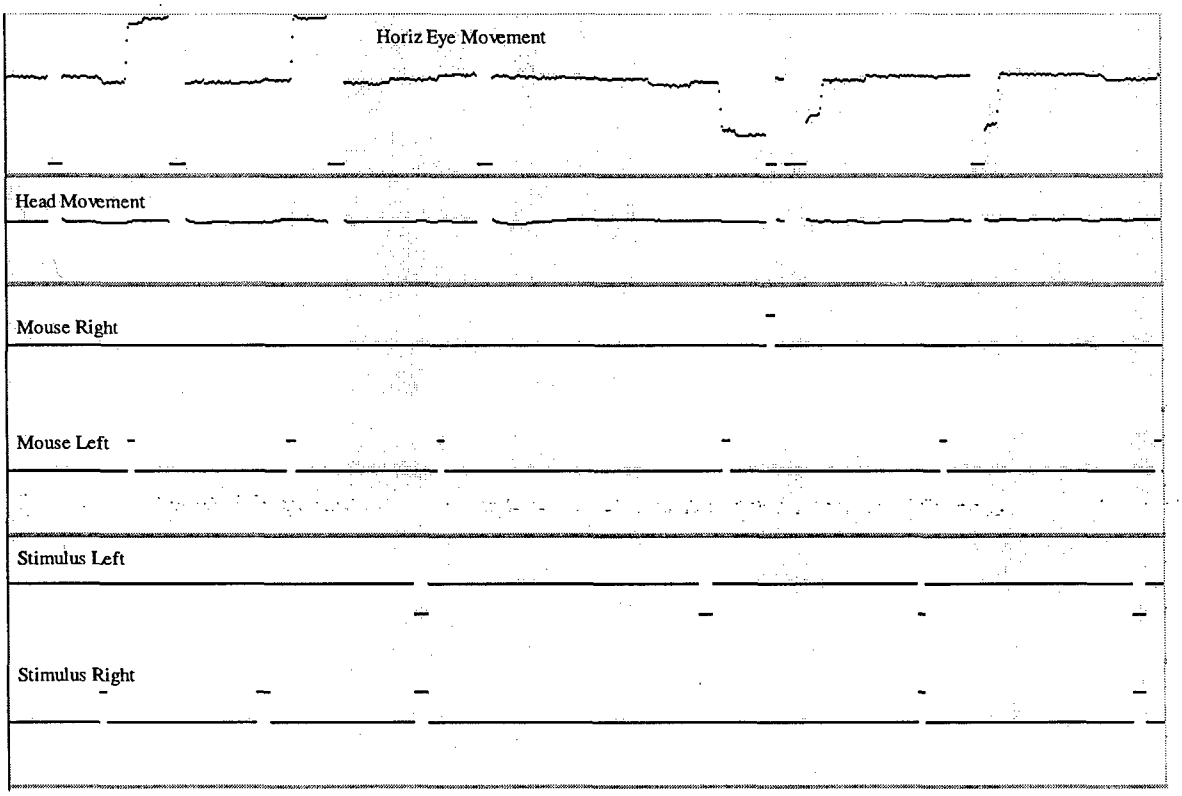


Figure 8 – Data traces for subject F12, 17 seconds starting at time 194 seconds

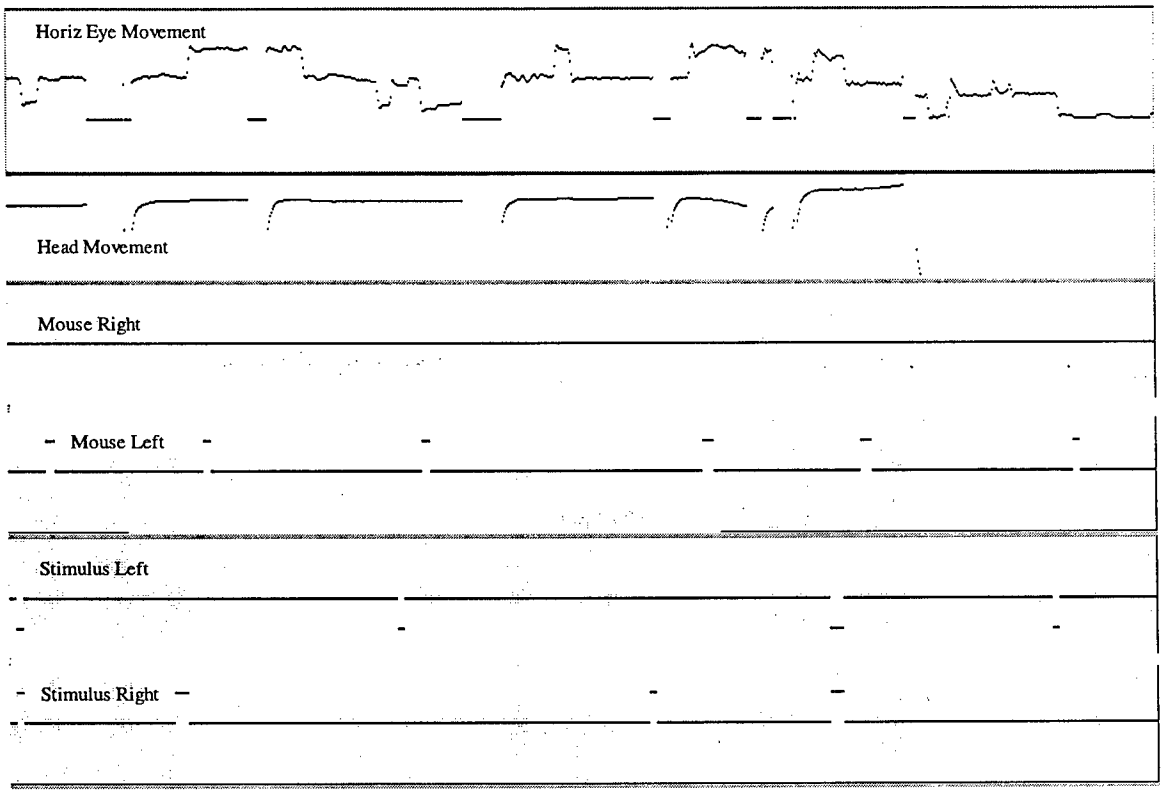


Figure 9 – Data traces for subject M13, 17 seconds starting at time-2573 seconds

5.3.3 Head movements associated with saccades

These head movements are inferred from changes in the calculated position of the center of the eyeball. The only way it can change is if there is a head movement. The observed movements are never greater in amplitude than 5% of the gaze shift, and in most instances do not exceed 2%. We have assured ourselves that these movements are not artifacts of the software used to identify gaze location. We did this by concurrent collection of gaze information and head movements identified using the LDV. We attached a small "flag" to the center of the forehead, aimed the laser at the flag and monitored head position in the horizontal plane. There was a high level of coincidence of the LDV and camera-based head movement measure. This reassured us that we were dealing with minor head movements and not noise.

Such head movements are seen in conjunction with tT saccades. Initiation of the head movement component is generally tightly coupled to saccade onset with termination usually later than saccade termination. Though we had expected a dissociation of the initiation time of these two measures as a function of ToT, our preliminary analyses do not find this to be the case. We propose further analyses to document this observation.

We have not systematically evaluated head movements associated with other than tT saccades. Though not dramatic, one can see head movements associated with gaze shift in Figure 8. The

first stimulus (to the right) has a minor head movement concurrent with the gaze shift to the right. A similar minor head movement can be seen associated with the gaze shift to the right for the next stimulus.

5.3.4 Pupil diameter measures reflecting performance impairment.

Pupil diameter will be a most important measure in the identification of attentional lapses.

Two types of analyses were performed on the pupillary measure, one dealing with ToT effects (tonic activity measure); the other dealing with the issue of differences in pupillary activity associated with lapses in performance as indexed by long latency SRT responses (phasic activity measure).

5.3.4.1 Tonic activity measure

There is suggestive data in the literature that fatigued individuals have both smaller pupils (Loewenstein and Loewefeld 1964) as well as greater variability in pupil diameter (Yoss et al. 1970). The greater variability in pupil diameter has been labeled "pupillary hippus". It is observed when subjects are required to sit in a darkened room for a 30-minute period and look at a dimly lit spot in front of them. We wondered whether this phenomenon was situation specific or if it could be observed under conditions of task performance. For the present analysis, we sampled the pupil every 17 seconds and averaged those measures in 5 minute increments. If no data was available at the midpoint of the 17-second period because of blinks or other reasons for data loss, we sampled the data shortly after it again became available. Where data was lost for a 17 second period we reduced the number of samples in the data set.

The information abstracted was average pupil diameter per 5-minute segment and variability as measured by S.D. in each five-minute segment. The following figures, Figure 10, Figure 11, and Figure 12, demonstrate the results for three subjects. Subject M22 demonstrates pupillary diameter decreases over the 60-minute period of task performance, as well as increases in variability as reflected in the S.D. As pupil diameter decreased, S.D. increased. Subject M15 also demonstrated pupil diameter decreases over time, though not as dramatic as the changes seen for M22. On the other hand, variability was every bit as dramatic for this subject as M22. Subject M14 demonstrates a pattern quite different from the other two in that he demonstrates an increase in pupil diameter as a function of ToT. Note, however that the measure of variability demonstrates an increase as a function of ToT. We will, in the near future complete the analysis of data for all 20 subjects. Should the remaining subjects demonstrate a pattern of pupil diameter change similar to that demonstrated by all three of the presented subjects, we will then go ahead and conduct spectral analysis of the data using a procedure similar to that used by McLaren et al. (1992).

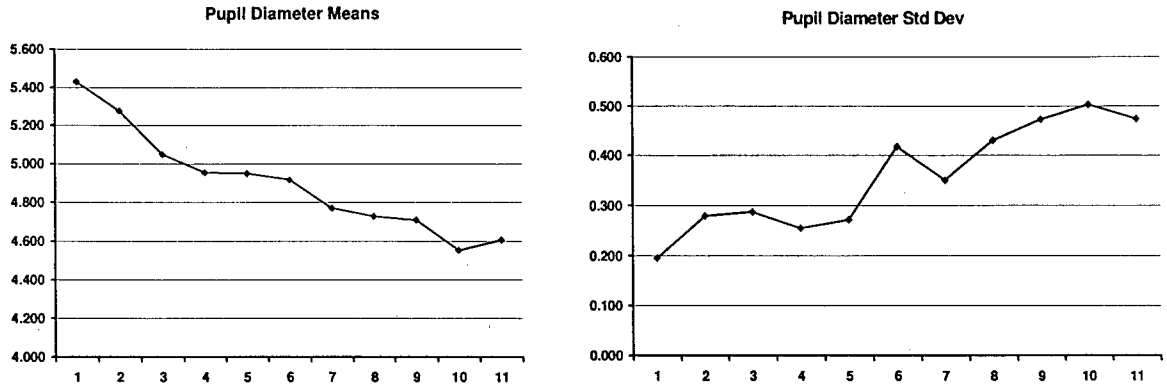


Figure 10 - Subject M22 - Pupil diameter mean and s.d. as a function of ToT

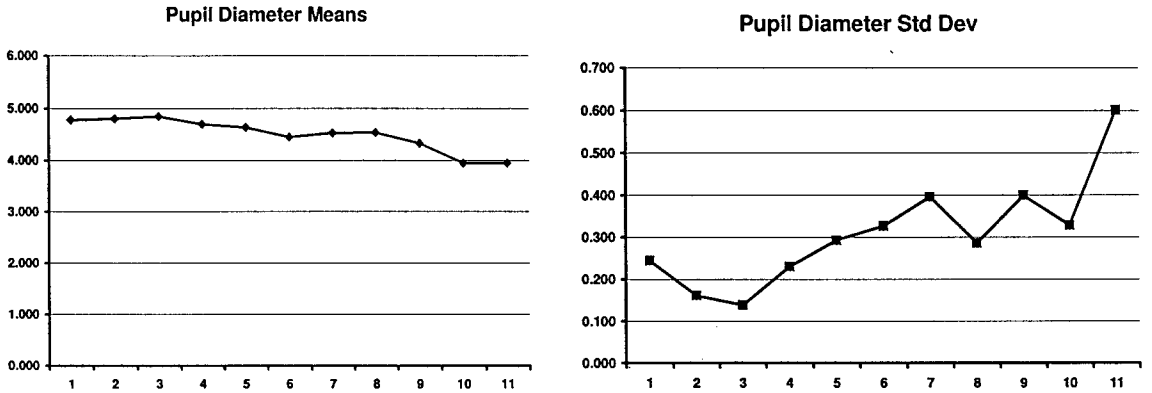


Figure 11 - Subject M15 - Pupil diameter mean and s.d. as a function of ToT

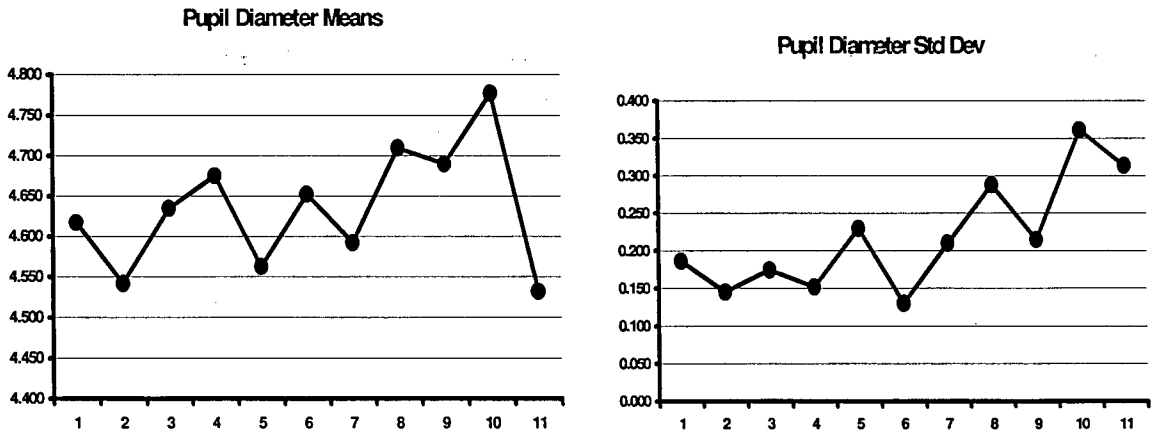


Figure 12 - Subject M14 - Pupil diameter mean and s.d. as a function of ToTm14

5.3.4.2 Phasic activity measure

We assumed that when subjects are responding slowly to the SRT task they are at a lower level of alertness than when they are responding "normally". Taking this one step further allows us to suggest that when subjects are responding rapidly, the pupil should be larger than when they are responding slowly, and hopefully larger than when they are responding "normally". In addition, we suggested that the enactment of a response might be alerting to subjects who were at a low level of alertness at time of stimulus presentation. This should be associated with an increase in pupil diameter for long latency responses. Pushing this a bit further, we would like to suggest that when subjects are reasonably alert at time of stimulus presentation, there should be no change or perhaps a decrease in pupil diameter following response initiation. They know that the next stimulus will not come immediately following their response and thus can relax briefly before the next stimulus occurs. To evaluate these "speculations" we performed the following analyses.

We identified the 50 slowest and 50 fastest responses for each subject (out of approximately 1200 SRT responses) and sampled 50 events close in time to the slowest responses and where the stimulus was at the same location as the long latency response. In addition to sampling pupillary data at stimulus presentation, we also sampled it at response onset, as well as at 340 milliseconds and 1020 milliseconds following response onset. Where no data was available because of lid closure or other reasons, we sampled the data close in time to the event in question. If data loss was for an extended period, i.e. included stimulus and response onset, that data was deleted. When we sampled at a point in time other than the initiation of stimulus and response onset and the two points beyond response onset that data was flagged. We have completed the analysis for all 20 subjects used as the data base for our evaluations. Figure 13 depicts the results of these analyses. Repeated measure analyses of variance of the three data points associated with stimulus onset, short, normal, and long latency responses was significant at beyond the 0.000 level and paired comparisons identified all paired comparisons as being significant.

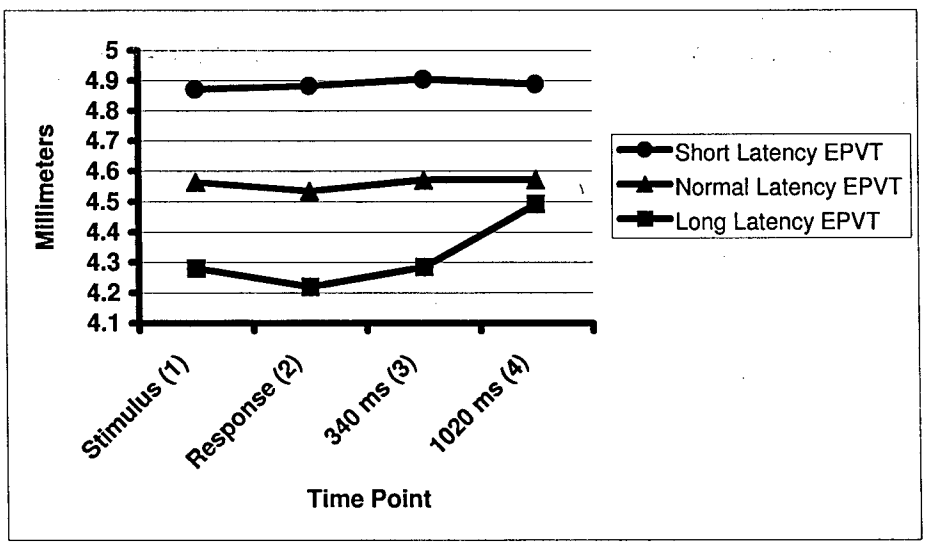


Figure 13 – Pupil diameter values near stimulus presentation for short, normal, and long latency responses

Similar analyses were conducted at response onset as well as the two points beyond response onset. The analyses for response onset and 340 milliseconds post response produced the same results as the analysis to stimulus onset. The analysis of data sampled 1020 milliseconds after response onset finds no difference between the long and normal latency response data while both are significantly different from the short latency response data.

What does the individual pupillary response look like? We present data from one subject who provides us with many events where a long latency response is associated with the pupil being small at time of stimulus presentation. Not all subjects demonstrate as nice a pattern as seen in this subject.

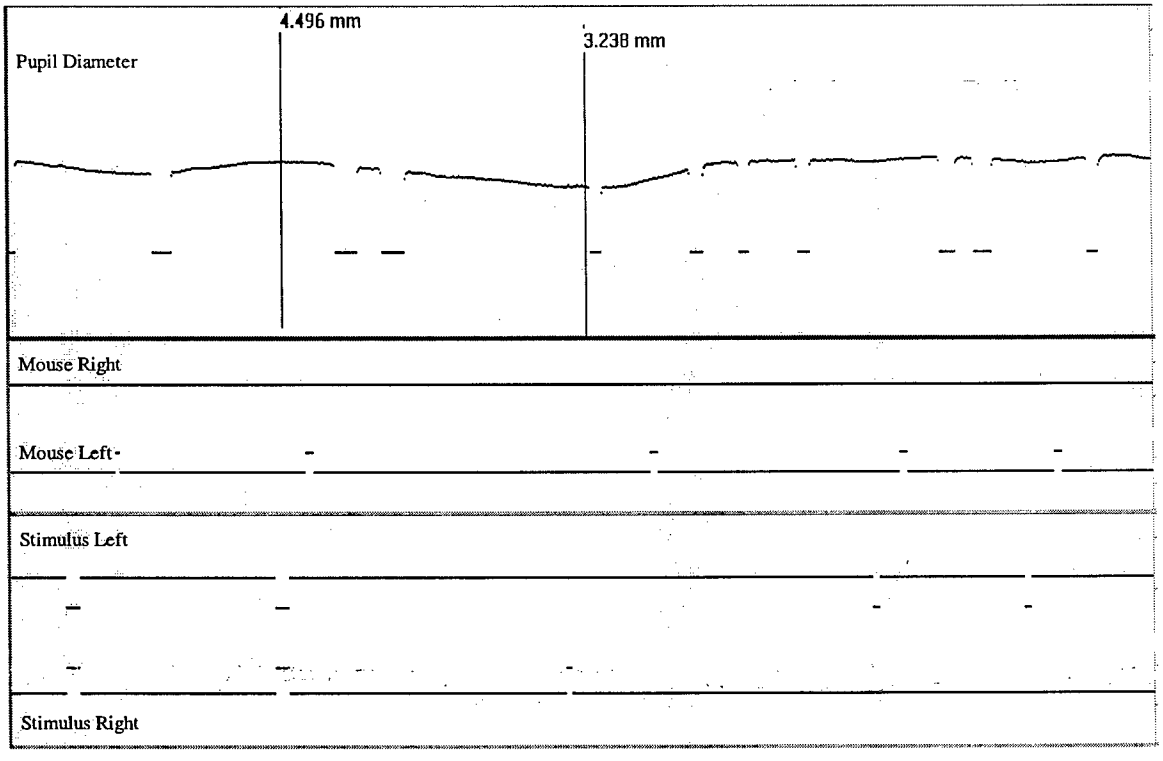


Figure 14 – Data traces for subject F10, 17 seconds starting at time 2014 seconds

In Figure 14, the third stimulus (right), a stimulus with a long latency response, has pupil diameter of 3.238 mm at the point immediately preceding a blink. This blink follows stimulus onset and occurs before response onset. For comparison, we have identified pupil diameter at a point prior to the initiation of the pupil constriction response. Pupil diameter at this point is 4.496 mm. The decrease in pupil diameter between these two points is 1.258 mm.

In Figure 15, following the response to the first stimulus (center), we have a series of eyelid closures as well as blinks. Pupil diameter at the point of response initiation for the second stimulus (right), a stimulus with a long latency response, is 3.314 mm. The two other measures of pupil diameter are provided to give some idea of the pupil constriction response preceding long latency responses. Note that following this long latency response the subject goes back to demonstrating normal duration blinks as well as normal latency responses.

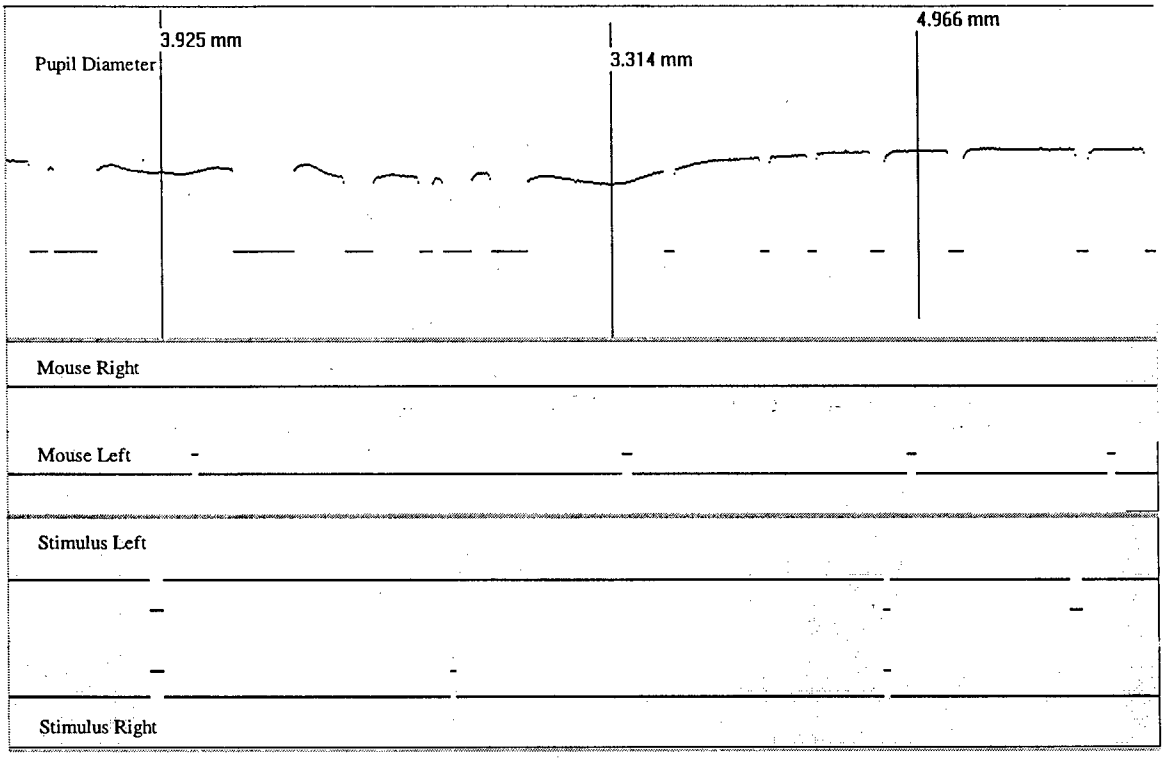


Figure 15 – Data traces for subject F10, 17 seconds starting at time 2214 seconds

5.4 Cardiovascular measures

5.4.1 Cardiovascular measures associated with "expectancy"

Description of analyses performed

This analysis dealt with the evaluation of cardiac activity during periods of "expectancy" or anticipation. Prior research from our as well as other laboratories has demonstrated that heart period duration increases when subjects are anticipating a relatively infrequently occurring event (Sirevaag, et al. 1999). We sought to confirm this in the preliminary data collected with the EPVT.

Data was evaluated for five subjects. For four of the subjects, the analysis was conducted on data collected with the LDV, and we used the opening of the aortic valve to trigger identification of the inter-beat interval. For the fifth subject standard ECG data was available and the peak of the R wave was used to identify IBI's. Data analysis utilized a computer routine for identifying the peak of the R wave and was manually edited for artifacts. The major purpose of this analysis was to determine whether we could reliably collect cardiovascular data with the LDV under the conditions of this experiment. The answer to the latter question is YES.

The first analysis of heart period change associated with anticipation involved measuring the duration of the five heart periods preceding and following occurrence of a third odd integer (O-O-O-R). Since anticipation was not limited to the occurrence of three odd integers, but

anticipation that the integer following a series of two odd integers would be odd, a further analysis was conducted on the five beats preceding and following the memory task response where no response was required, i.e. high level of expectation and disconfirmation of the expectation (O-O-E- no response).

It was expected that anticipation of the third odd integer would lead to lengthening of the heart period. In our earlier study the inter-stimulus interval was constant, subjects could thus not only anticipate the occurrence of an event requiring a response but also could anticipate time of occurrence. In the present study the inter-stimulus interval was varied so that anticipation of when a stimulus occurred was not available.

We evaluated the inter-beat interval (IBI) for the five periods preceding onset of the third integer, the period involving presentation of the third integer and the five periods following the third integer. (Since the inter-stimulus interval varied around an average of 2.5 s, this analysis frequently included periods where stimuli were presented.) Three analyses were conducted, one for the situation where a response was required and enacted (with response), one for events where a response was required but not made (missed signal – no response) and for the situation where two odd integers were followed by an even integer (3rd even). The analysis was conducted both for "raw" data as well as for "normalized" data. Data was normalized using, for each subject, the average of the first IBI as the "comparison" value and expressing successive average values for each individual as a percentage of the first interval. An analysis of variance was done on heart period duration following normalization. The results demonstrated a significant difference across the inter-beat intervals with a $p < 0.01$.

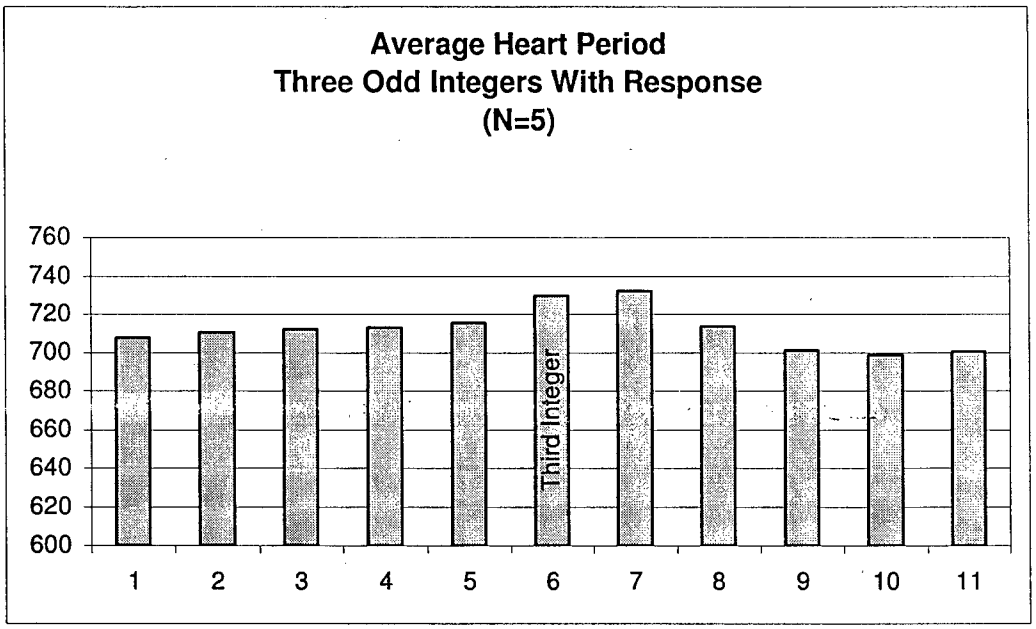
Figure 16 depicts the results of the heart period analysis both for average (i.e. "raw" heart periods) as well as normalized values under the condition in which a response to the memory task was required.

As depicted in both Figure 16 and Figure 17, the heart period for the interval involving presentation of the third integer and for the interval following it demonstrate a lengthening of heart period for both the conditions where a response was required and made, and the condition where anticipation of the third odd integer was disconfirmed and no response was made. The analysis of variance showed a significant difference between the heart periods with a p-value of < 0.01.

In the "with response" condition we evaluated, for each of the 20 trials analyzed for each subject, the period in which the longest inter-beat interval occurred. For two subjects, the heart period preceding the response was most often the longest. In the other three subjects this heart period contained the longest period the second most times.

The next analysis evaluated the condition where two odd integers were followed by an even integer. Approximately 30 occurrences of this sequence were analyzed for each subject.

An analysis across all subjects demonstrated cardiac deceleration in the interval containing the third (even) integer, and the period directly following it. The pattern was similar to that seen in the analysis above. An analysis of variance done on the data from all subjects after normalization showed a significant difference with $p < 0.01$.



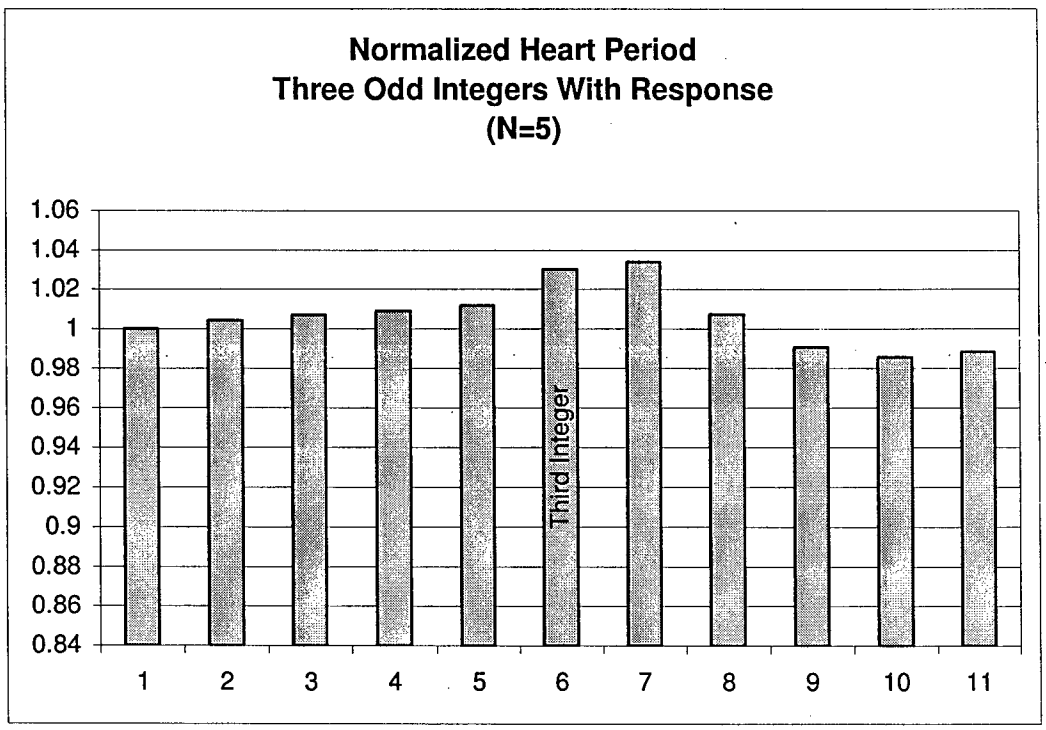


Figure 16: Raw and normalized heart period for 3 odd integers with memory task response required

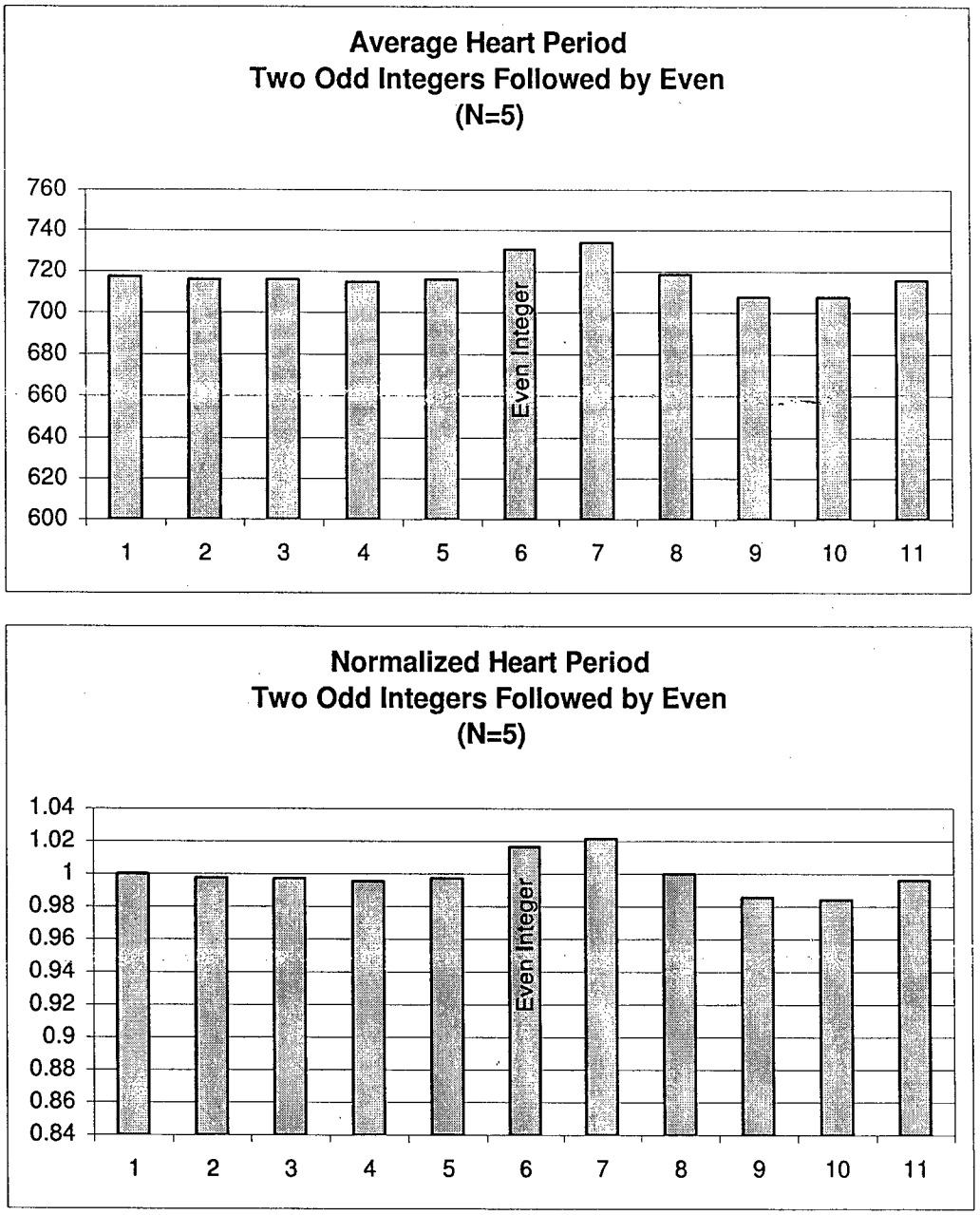


Figure 17: Raw and normalized heart period for 2 odd integers with memory task response not required

The last analysis was conducted to determine if heart period slowing occurs when a subject should be showing anticipation but does not. These instances occur when a sequence of three odd integers is not followed by a response. This event occurred relatively infrequently and the average number of such events was 5.4 times per subject. This analysis was done with the five heart periods before the third odd integer and the seven periods after the integer. No significant effects were obtained. Figure 18 suggests a decrease in heart period both preceding and following presentation of the third integer, but these effects were not reliable.

After all three conditions were analyzed, a further analysis was done comparing the three conditions (O-O-O-R; O-O-O-no response; and O-O-E-no response). An analysis of variance was done across all three groups to determine if there was a significant difference in the pattern. The results showed a difference with a $p< 0.01$ in the normalized data. Subsequently, t-Tests were conducted. They demonstrated no differences between the correct response condition and the condition with the third integer even ($p>.2$) for any of the comparisons. The t-Tests demonstrated that the condition with three odd integers and no response was significantly different from the other two conditions ($p<0.05$).

Figure 19 shows both the raw average heart period and the normalized heart period data for all three conditions.

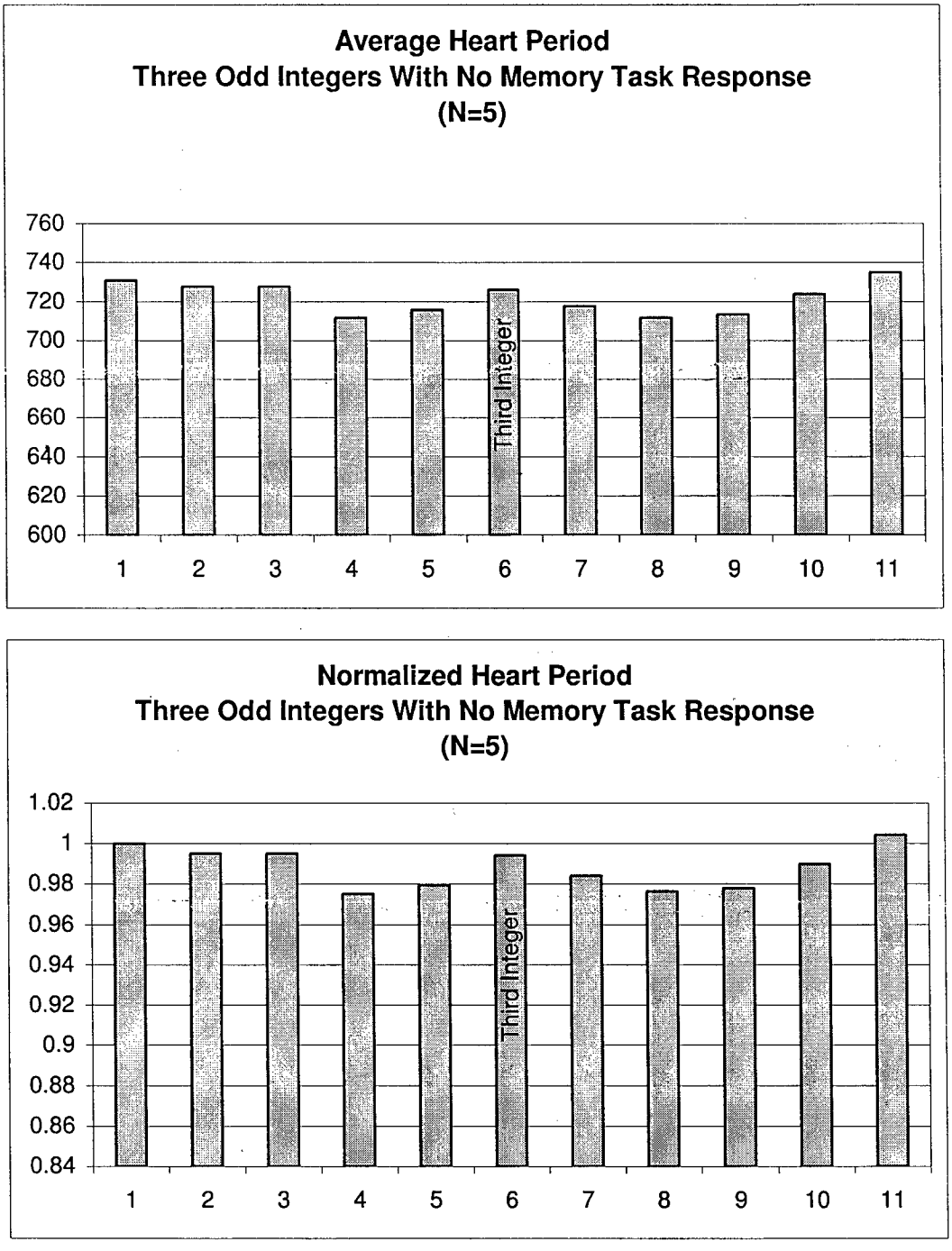


Figure 18: Raw and normalized heart period for 3 odd integers with no memory task response

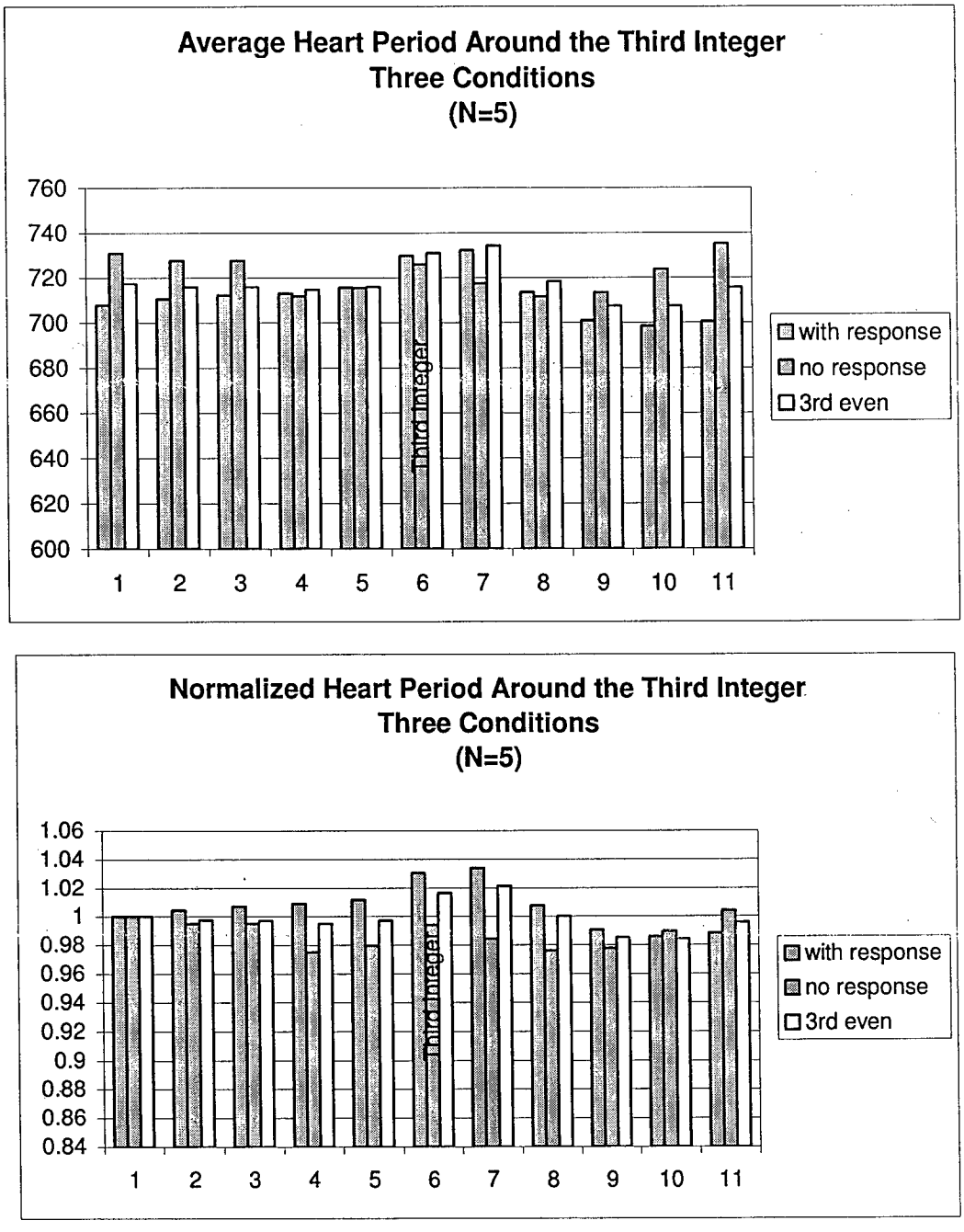


Figure 19: Raw and normalized heart period for all three conditions described

Discussion

Previous research (Lacey, 1974; Jennings, 1992; van der Molen, 2000; Somsen, 2004) using principally fixed foreperiod reaction time tasks demonstrated that in response to visual stimuli and anticipation the heart rate of a subject will slow. The studies show that the anticipation

response is greatest when stimulus onset is predictable. It is attenuated in conditions where timing of stimulus presentation is not predictable, as was the case in our study. Our data support the contention that the effect is still present when stimulus timing is not predictable. We show that when subjects are correctly anticipating (the correct response condition, and the no third odd integer condition) heart rate slows in response to the third integer. In the condition where subjects should be responding but fail to respond, such cardiac slowing is not present. Our results thus demonstrate that it is the anticipation of a stimulus requiring a response and not the enactment of the response that is responsible for the cardiac deceleration. When anticipation is not present, i.e., the condition where a response is required but not made, the cardiac slowing does not materialize.

This slowing is presumed to be due to vagal stimulation of the heart, this supposition has in turn been supported by empirical physiological evidence (Somsen, 2004). Previous studies by Lacey (1974, 1977, 1978) and a review of this and other studies by Somsen (2004) demonstrate that a visual stimulus can affect the inter-beat interval (IBI) if it is presented early enough in the interval, or the interval directly following it if it is presented in the later part of the IBI. In the present study, no attempt was made to have stimulus presentation coincide with a particular phase of the cardiac cycle. The wider distribution of heart period increase found in associated with anticipation may reflect the fact that the imperative stimulus was presented at random phases in the cardiac cycle.

Since our LDV technology in combination with EKG will allow us to fractionate the cardiac cycle into three components (pre-ejection period; ejection period; recovery period) we will be able to determine whether all components of the cardiac cycle are equally affected by "anticipation" or, as we suspect, the effect will discriminate between the three components.

5.4.2 Fractionation of heart period into; pre-ejection; left ventricular ejection, and post ejection periods.

There is no research literature dealing with these measures since they can normally only be obtained by invasive procedures. We wondered whether there would be changes in the proportion of time occupied by these components as the interbeat interval increased. This analysis, at the present time, is partially computerized and partially under operator control. Thus only relatively few comparisons have been made.

The first investigation asked whether heart period slowing associated with periods of non-responding to the task had a similar distribution of these components as heart period slowing associated with expectancy (see section 5.4.1 above). For a limited data sample, we were not able to identify major differences in these components across the two conditions. Further analyses will be conducted.

We are also evaluating heart period variability as a function of ToT. This evaluation is based, in part, on our finding of pupillary hippus increasing as a function of ToT. We are sampling the ECG for successive 5-minute periods and calculating both mean and standard deviation of the interbeat interval. For the few subjects evaluated to date, there appears to be an increase in variability as a function of ToT. This might then become an additional measure for the evaluation of tonic effects indicative of fatigue.

What does the LDV cardiac signal look like? Figure 20 provides an example. The first channel is a standard ECG; the second is the concurrently recorded LDV signal from the carotid artery. The first major peak in the LDV signal identifies onset of the opening of the aortic valve, the next major peak, with a dicrotic notch, identifies the closing of the valve. In combination with the ECG, we can thus identify the pre-ejection period (from peak of ECG r-wave to the first peak in the LDV signal; the left ventricular ejection period (from onset of the first LDV peak to the onset of the dicrotic notch) and a final "rest" period. Displayed are 4 seconds of data.

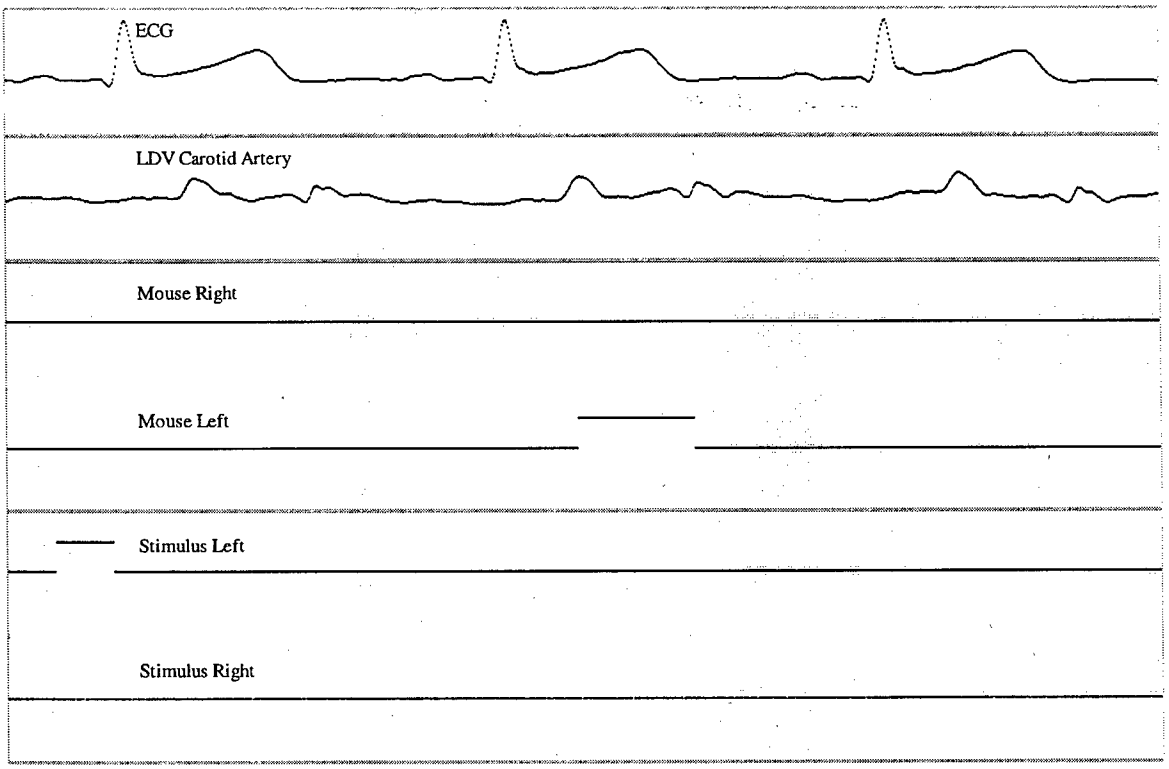


Figure 20 – Data traces for subject M13, 2 seconds starting at 952 seconds

6 Conclusions

The EPVT task developed for this project appears to be sensitive to time on task effects even with well-rested subjects. We have demonstrated the capability for recording oculomotor as well as Laser-Doppler Vibrometry data under these conditions. We further have demonstrated significant time on task effects for the bio-behavioral measures employed. Analysis of data from some biological systems was completed for the twenty subjects. We were able to demonstrate that pupil diameter was an excellent reflector of lapses in alertness. When subjects were at a lower level of alertness, as reflected by long latency reaction time responses, pupil diameter was significantly smaller at time of stimulus onset, as well as at response onset, than when response latencies were "normal" or rapid. Heart period data demonstrated that anticipation of responding to the running memory task produced significant slowing of heart rate. This is concordant with the literature. We are well along in specifying both hardware and software requirements to allow for the on-line analysis of bio-behavioral signals of interest.

7 References

Dinges, D.F. & Kribbs, N.B. (1991). Performing while sleepy: effects of experimentally-induced sleepiness. T.H. Monk (ed) *Sleep, sleepiness and Performance*, Wiley, New York, N.Y.

Jennings, J. R. (1992). Is it important that the mind is in a body? Inhibition and the heart. *Journal of Psychophysiology*, **29**, pp. 369–383.

Lacey, B. C., & Lacey, J. I. (1974). Studies of heart rate and other bodily processes in sensorimotor behavior. In P. A. Obrist, A. H. Black, J. Brenner, & L. V. DiCara (Eds.), *Cardiovascular Psychophysiology*, pp. 538–564.

Lacey, B. C., & Lacey, J. I. (1977). Change in heart period: A function of sensorimotor event timing within the cardiac cycle. *Physiological Psychology*, **5**, pp. 383–393.

Lacey, B. C., & Lacey, J. I. (1978). Two-way communication between the heart and the brain: Significance of time within the cardiac cycle. *American Psychologist*, **33**, pp. 99–113

Lowenstein, O. & Loewenfeld, I.E. (1964). The sleep-waking cycle and pupillary activity. *Annals of the New York Academy of Science*, **1**, 142-156.

McLaren, J.W., Erie, J.C. & Brubaker, R.F. (1992). Computerized analysis of pupillograms in studies of alertness. *Investigative Opthalmology Visual Science*. **33**, 671-676.

Sirevaag, E.J., Rohrbaugh, J.W., Stern, J.A., Vedeniapin, A.B., Packingham, K.D. & Lajonchere, C.M. (1999). *Multi-dimensional Characterization of Operator State: A Validation of Oculomotor Metrics*. U.S. Department of Transportation DOT/FAA/AM-99/28.

Somsen R.J., Jennings J.R., Van der Molen M.W. (Nov 2004). The cardiac cycle time effect revisited: Temporal dynamics of the central-vagal modulation of heart rate in human reaction time tasks. *Psychophysiology*. **41(6)**, pp. 941-953.

Van der Molen, M. W. (2000). Developmental changes in inhibitory processing: Evidence from psychophysiological measures. *Biological Psychology*, **54**, pp. 207-239.

Wilkinson, R.T. & Houghton, D. (1982). Field test of Arousal: A portable reaction timer with data. *Human Factors*, **24**, 487-493.

Yoss, R.E., Moyer, N.J., & Hollenhorst, R.W. (1970). Pupil size and spontaneous pupillary waves associated with alertness, drowsiness, and sleep. *Neurology*, **20(6)**, 545-554.

Appendix A: Related Paper Recently Presented at SPIE

The gaze control system: reflector of cognitive activity

Erik J. Sirevaag*[a], John A. Stern[b]
[a]Dept. of Psychiatry, Wash. Univ. Med. School, 4625 Lindell, Suite 2, St. Louis, MO USA 63108
[b]Bio-Behavioral Analysis Systems, LLC, 7472 Woodlawn Colonial Ln, St. Louis, MO USA 63119

ABSTRACT

A hybrid sustained attention task was developed in order to examine the relationships between manual response times and the timing and morphology of horizontal saccades involved in shifting gaze to a source of task relevant visual information. Twelve subjects performed this task for 60 min with no breaks. Performance and gaze control measures were aggregated across 20 min intervals comprising early, middle and late segments of the task. Response time variability was significantly increased during later task segments ($p<0.05$). These segments were also associated with increased variability in the amplitude of saccades ($p<0.05$). Saccade durations during the late task segments were also longer and more variable ($p<0.05$). Correlations between response times and measure of saccadic activity were also computed across consecutive 5 min intervals for each individual subject. The obtained correlations between saccade latency and response times exceeded 0.70 for six of the twelve subjects. Additional analyses examined the relationship between trials characterized by extreme values on either the performance or the gaze control measures. Trials characterized by extremely long response times were also associated with increased saccade amplitudes, durations and latencies ($p<0.01$). Conversely, response times were abnormally long on trials categorized as extreme on the basis of the saccade morphology and timing measures ($p<0.01$). These results confirm the utility of the sustained attention task as a laboratory platform for the development of real-time systems for alertness monitoring. The data also support the contention that measures of gaze control behavior can reflect aspects of cognitive activity and, therefore, should be seriously considered for inclusion in any physiologically-based alertness assessment battery.

Keywords: gaze control, saccades, oculomotor, vigilance, fatigue, cognition

1. INTRODUCTION

Many tasks in a variety of operational settings require individuals to monitor aspects of the environment and infrequently intervene in the ongoing operation of a particular system. An operator's ability to maintain a high level of performance under such "vigilance" conditions is limited. Deficits in performance increase as a function of Time-On-Task (TOT) and typically become manifest within the first hour of task performance. However, the decline in performance is typically not a linear function. Instead, increases in the frequency and/or duration of behavioral lapses, or blocks, surrounded by periods of relatively normal performance are typically found with increased TOT[1].

A key issue is whether these performance lapses are reliably associated with or preceded by physiological signs predictive of impending performance impairments. Our research program has been designed to address three key issues. First, can laboratory tasks be used to identify measures associated with performance blocks? Second, can the results obtained in the laboratory be extrapolated to real-world environments? Finally, can these measures be obtained and evaluated in real-time to provide instantaneous evaluations of operator alertness and/or cognitive load? The ultimate goal of this program of research is the development and validation of a real-time alertness monitoring system. Furthermore, in order to assure the widest possible applicability in real-world environments, the proposed system will rely upon non-contact sensors for monitoring physiological processes and will not impose additional demands (i.e. "secondary tasks" unrelated to the normal operational environment) upon the operator. Such a system would have a wide range of applications in areas as diverse as fitness for duty assessment; adjustment of the optimal level of automation in man-machine systems; titration of task difficulty during computer-aided learning; the evaluation of operator alertness/efficiency during sustained performance and/or following sleep deprivation, etc.

Measures of oculomotor activity are attractive candidates for inclusion in a real-time alertness assessment battery. The gaze control system is intimately involved in the acquisition and processing of information[2]. The direction of gaze, the

duration for which gaze is directed at a given location, and the speed with which the eyes move to a target location all reflect aspects of information processing and attention. Movements of the head also participate in the acquisition of visual information and can, therefore, potentially provide additional insights into the processing demands associated with task performance. The behavior of the eyelids is also sensitive to aspects of information processing. The frequency, duration as well as the timing of blinks with respect to external events can provide a great deal of information about the current state of an operator. Pupil diameter change as a reflector of variables such as workload and other cognitive operations can also be obtained with most camera-based systems. Importantly, the advent of camera-based eye trackers means that many aspects related to gaze control can be measured in real-time without the application of electrodes or other obtrusive transducers.

Measures of gaze control can be further divided as a function of whether the oculomotor activity in question is specifically tied to elements of the task being performed by the operator. For example, the PERCLOS measure of lid closure[3] and other metrics such as blink frequency do not depend on the architecture of the specific task being performed by the operator. In contrast, measures of blink and saccade inhibition as a consequence of the anticipation of the delivery of task-relevant information cannot be obtained in the absence of knowledge concerning the dynamics of the task being performed. The latency of saccadic eye movements directing gaze to the location of a source of mission critical information is another example of a task-specific measure of gaze control. We believe that both general and task-specific aspects of gaze control behavior will be important components of our real-time assessment battery. In this report, we focus upon attempts to relate performance on a sustained attention task to aspects of a task-specific component of gaze control -- namely To Target (TT) horizontal saccades which shift gaze to a source of task relevant visual information.

To this end, a hybrid sustained attention task was developed. Our Enhanced Psychomotor Vigilance Task (EPVT) consisted of a simple visual Reaction Time (RT) task, similar to traditional PVT paradigms[4], differing by the addition of spatial and memory task components. Subjects performed this task continuously for 60 min. Relationships between RT and TT saccade timing and morphology were evaluated across consecutive 20 min intervals and also across consecutive 5 min intervals. Additional analyses focused upon groups of trials identified as extreme (very fast vs. very slow RTs, for example) were also conducted.

2. METHODOLOGY

2.1 Subjects

Twelve individuals (8 male, 4 female) ranging in age between 18 and 25 years participated in the study. All subjects were in good health and possessed normal or corrected-to-normal vision (no contact lenses) and hearing. The subjects were screened for previous history of head trauma and neurological disorders.

2.2 Tasks and stimuli

The EPVT required subjects to respond as quickly as possible (by pressing the left button on a mouse) following the activation of a timer presented either in the center of the screen or offset 10 degrees to the left or right of the midpoint. The manual response terminated the timer and the resulting Reaction Time (RT) information remained displayed for 400 msec. The interval between the disappearance of the RT feedback and the presentation of the next stimulus varied between 1.5 and 3.5 sec (mean interval = 2.5 sec). If no response occurred within 4000 msec the trial was labeled a miss. A second response (depression of the right mouse button) was required following three successive reaction times ending in an odd integer. The value of the last digit of the displayed RT was under experimenter control and was manipulated so that 48 events involving the occurrence of three odd integers and 96 instances of two odd integers followed by an even integer were equally distributed across the 60 min duration of the task. This eye-movement rich task, therefore, embodied both simple RT (frequent responses to timer presentations) and memory task (infrequent responses to three consecutive odd RTs) components.

2.3 Apparatus

Oculomotor behaviors (horizontal and vertical movements, pupil diameter and head movements) were monitored using a camera-based eye tracking system (EyeGaze – L.C. Technologies Inc., Fairfax VA). Analog signals from the eye-tracking system and event-markers indicating the timing of task stimuli and subjects responses were digitized using a

BIOPAC MP100 (Linton Instrumentation UK) workstation. The analog data were continuously sampled at 2000 Hz and stored to disk using the Acknowledge Software (version 3.8.1) associated with the MP100 system.

2.4 Procedure

Each subject participated in a single session which typically lasted 2 hours. Sessions began at 10am, noon, 2pm or 4pm (session start times distributed equally across subjects). Upon arrival in the laboratory, subjects filled out an informed consent form as well as a battery of questionnaires designed to assess their current mood, level of alertness, sleep habits and the quality of sleep the preceding night. The eye-tracker system was then calibrated and the subjects were presented with a written set of instructions detailing the requirements of the EPVT. A five min practice task was then conducted to insure that the subjects understood the instructions and that the equipment was working properly. The practice block was followed by 60 min of continuous performance on the EPVT with no breaks during this period.

2.5 Analyses

Analyses were focused upon measures of gaze shifts which moved the eye to the location of the most recently activated, peripherally located timer. Software developed in the authors' laboratory [Bio-Behavioral Data Reduction System (BBDRS) version 5.5.4, Bio-Behavioral Analysis Systems, LLC] was utilized to identify and isolate TT saccades as well as to quantify the amplitude and duration of these saccades using standard algorithms described elsewhere[5]. In addition, TT saccade latency (interval between the activation of a timer and the initiation of an eye-movement to that location) was also computed. The amplitude of minor head movements associated with gaze shifts was inferred from the center-of-the-eyeball coordinates computed by the eye-tracking system. Simple RT was computed as the latency of the button press response following the activation of a timer.

Questions concerning the consequences of increased Time-on-Task (TOT) upon these gaze control and performance measures were explored by segmenting the 60 min of continuous performance into three 20 min intervals designated "Early", "Middle" and "Late". TOT effects were statistically evaluated by submitting measures from these time points to a single factor repeated measures Analysis of Variance (ANOVA). The degrees of freedom were adjusted using Geisser Greenhouse corrections for violations of the sphericity assumption. Planned contrasts between the three task intervals were conducted using a modified Bonferonni technique[6]. Given the exploratory nature of this project, contrast analyses were conducted for all significant main effects ($p<0.05$) as well as for non-significant trends ($p<0.10$). More finely-grained analyses of the relationship between specific gaze control measures and performance were obtained by correlating the responses averaged across successive 5 min intervals throughout the duration of the task. Due to high variability in both the performance and oculomotor measures in the last 5 min block, these correlation analyses were restricted to the first 55 min of task performance.

The relationship between the control of gaze and performance was also assessed through the analyses of "extreme" trial groups, which were not explicitly defined in terms of TOT. Thus, for each subject, individual reaction times were sorted in order to select 20 trials in each of three categories. "Short RT" trials were defined as the 20 fastest RT trials. "Medium RT" trials were identified by selecting 20 trials centered around the mean RT for the entire run. Finally, "Long RT" trials were defined as the 20 longest RT trials. Measures of oculomotor activity associated with each of these three response categories were than computed and submitted to statistical procedures identical to that described for the analyses of TOT effects. Similar procedures were subsequently employed to examine the extent to which RT varied as a function of associated gaze control activity. Thus, mean RT was computed across twenty trials associated with "small", "medium" and "large" TT saccade amplitudes, "short", "medium" and "long" TT saccade durations, and "short", "medium" and "long" TT saccade latencies.

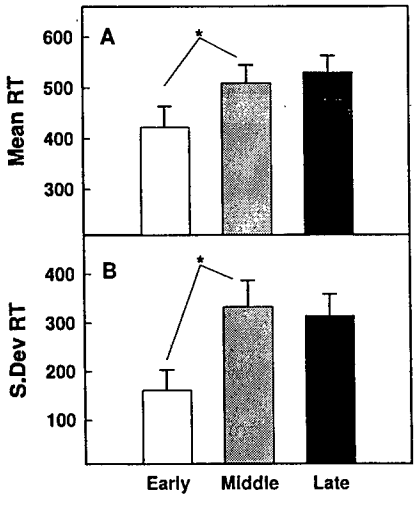


Figure 1: RT by Task Segment
*p<0.05

3. RESULTS AND DISCUSSION

3.1 TOT effects

3.1.1 RT measures

Performance, as indexed by the simple reaction time measure, was not constant throughout all 60 min of the task (see Figure 1). While the TOT effect just failed to reach statistical significance with respect to mean RT [F(2,22)=3.621; p=0.058], RT variability, reported as the standard deviation of RT) was sensitive to TOT [F(2,22)=4.746; p=0.029]. Inspection of Figure 1 reveals a trend towards longer RTs and increased response variability with increasing TOT (however only the differences between the first and last task segments could be statistically discriminated).

3.1.2 TT saccade measures

Results of the analyses of TOT upon the gaze control measures are presented in Table 1. Saccade duration was the measure most sensitive to the TOT manipulation. Saccade duration increased and became more variable with increased TOT. Mean saccade amplitude did not vary across the three task segments; however amplitude variability did increase with increasing TOT. The saccade latency measures were not sensitive to TOT. As can be seen in Figure 2, saccade amplitude variability increased significantly across all three (early, middle and late) task segments. Mean saccade duration and saccade duration variability showed a similar trend but only the early and late segments could be discriminated statistically. The saccade latency measures displayed a similar tendency to increase with increasing TOT, but the only difference to achieve statistical significance was between the early and late task segment on the latency variability measure.

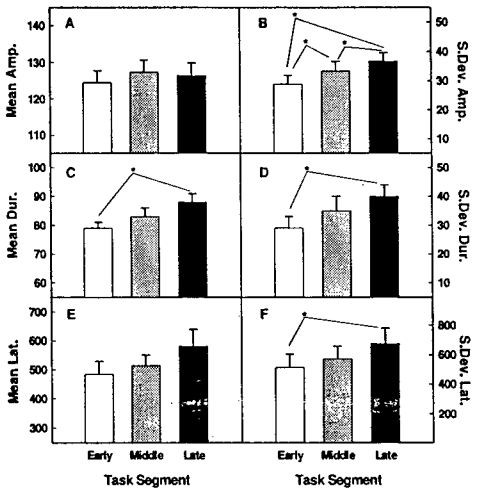


Figure 2: TT saccade measures by Task Segment. A) Mean Amplitude; B) Amplitude Variability; C) Mean Duration; D) Duration Variability; E) Mean Latency; F) Latency Variability. *p<0.05

TT Saccade Measure	F(2,22)	p-value
Amplitude (mean)	1.029	0.358
Amplitude (std. dev.)	14.844	0.001*
Duration (mean)	9.763	0.001*
Duration (std. dev.)	5.017	0.018*
Latency (mean)	2.179	0.137
Latency (std. dev.)	2.186	0.148

Table 1: TT Saccade by TOT ANOVA results
* p < 0.05

3.2 Correlations between performance and gaze control

The division of the task into early, middle and late segments, though not uncommon in the literature, represents a fairly coarse and somewhat arbitrary means of examining behavioral variability. To facilitate a more finely grained analysis of the relationship between local task performance and gaze control, mean RT and TT saccade characteristics were computed across consecutive five min periods. The correlations between RT and the gaze control measures were then computed across these intervals -- separately for each of the twelve subjects. The results of this analysis, presented in Table 2, clearly show that aspects of gaze control are quite predictive of RT. TT saccade latency was the best single predictor of local RT, with obtained correlation coefficients ranging between 0.71 and 0.94 for six of the twelve subjects. This comparison yielded coefficients lower than 0.37 for only two of the twelve subjects in the study. Interestingly, for both of these subjects, performance was correlated with either the TT saccade amplitude or latency measure at a value at or above 0.50.

	RT Correlations (Pearson's R)		
Subject	Saccade Amplitude	Saccade Duration	Saccade Latency
1	-0.25	0.58	0.94
2	0.88	0.70	0.85
3	0.16	0.10	0.87
4	0.20	0.44	0.39
5	-0.02	0.50	0.06
6	-0.61	0.92	0.71
7	-0.15	-0.05	0.38
8	0.61	0.39	0.84
9	0.52	-0.15	0.18
10	0.61	0.20	0.45
11	0.11	0.53	0.93
12	-0.38	0.22	0.37

Table 2: Single subject RT and saccade correlations

3.3 Extreme group comparisons

3.3.1 Segregation by RT

In this analysis, single trial RTs from the entire task were sorted. Gaze control measures associated with the 20 shortest and 20 fastest RTs were then computed. In addition, gaze control measures associated with 20 medium latency RT

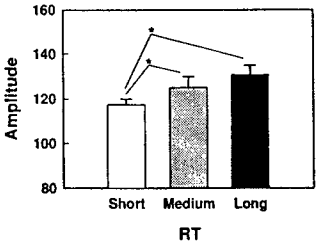


Figure 3: Saccade Amplitude by RT
*p<0.05

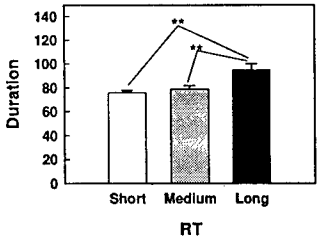


Figure 4: Saccade Duration by RT
**p<0.01

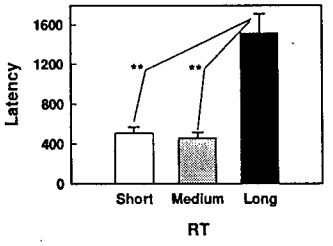


Figure 5: Saccade Latency by RT
**p<0.01

trials (centered upon the mean of the distribution) were also obtained. TT saccade amplitude [F(2,22)=5.733; p=0.014] , duration [F(2,22)=16.344; p<0.001] and latency [F(2,22)=37.407; p<0.001] all varied significantly as a function of associated RT. As demonstrated in Figure 3, short RT trials were associated with smaller amplitude TT saccades. Figures 4 and 5 reveal that the long RT trials were associated with longer duration and larger latency TT saccades than either the medium or short RT trials.

3.3.2 Segregation by gaze control measures

Extreme trial groups based upon gaze control data were constructed in a manner analogous to that just described for the RT distribution. Thus, RT differences were examined as a function of small, medium and large amplitude TT saccades; short, medium and long duration TT saccades; and short, medium and long latency TT saccades. Figure 6 displays the simple RTs associated with trials differing in the amplitude of the associated TT saccade. Although the main effect of amplitude group on RT just failed to reach significance [F(2,22)=3.194; p=0.061], pairwise comparisons of the group

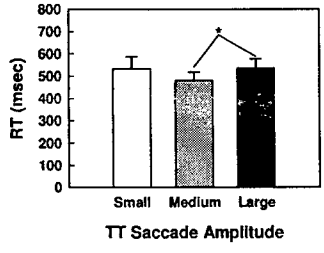


Figure 6: RT by Saccade Amplitude
*p<0.05

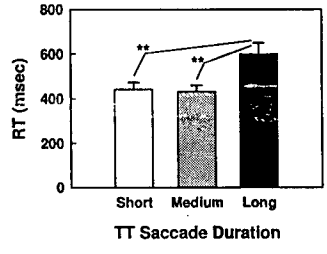


Figure 7: RT by Saccade Duration
**p<0.01

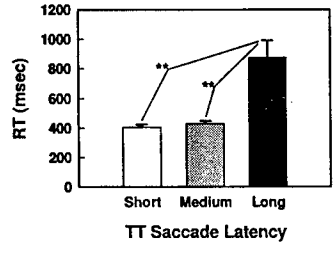


Figure 8: RT by Saccade Latency
**p<0.01

means indicated that the RTs for trials from large amplitude saccades were slower than the RTs associated with medium amplitude saccades. Figures 7 and 8 display comparable RT data for the groups segregated by the duration and latency measures. Main effects of both the duration [F(2,22)=9.416; p<0.001] and latency [F(2,22)=14.929; p<0.001] segregations were obtained. Long duration TT saccades were associated with increased RTs (as compared to both the short and medium duration groups). Similarly, RTs on trials classified as belonging to the short and medium latency TT saccade groups were significantly shorter than when the trial belonged to the long latency classification.

4. CONCLUSIONS

A number of conclusions can be drawn from the data presented above. Sixty min of continuous performance on the EPVT produced significant periods of performance drop-outs as well as associated increases in the variability of measures of gaze control. These performance lapses tended to occur with increasing frequency during later task segments resulting in a number of TOT effects on both the performance and gaze control measures. Thus, RT variability increased with increasing TOT while TT saccade durations lengthened and became more variable as a function of TOT. TT saccade amplitude variability also increased during later time intervals. Not surprisingly, aggregating data across 20 min segments proved too coarse an analysis interval for the detection of significant differences in TT saccade latency. However, the analysis of data collapsed across consecutive 5 min intervals revealed that TT saccade latency was highly predictive of local RT performance. The latency measure was the best single predictor of RT. Notably, for the two subjects who evidenced no relationship between the latency and RT measures, substantial correlations between RT and either the amplitude or latency measure were obtained. These findings establish the utility of the EPVT as a laboratory test-bed for the proposed real-time alertness monitoring system. However, the ultimate success of such a real-time system depends upon the existence of an even closer relationship between performance drop-outs and the control of gaze. Importantly, significant relationships between performance and gaze control measures were also obtained for groups of trials identified as extreme –irrespective of their time of occurrence during the performance of the task. Thus, trials with extremely long RTs were also characterized by increases in the duration and latency of the associated TT saccade. Conversely, increases in the amplitude, duration and latency of TT saccades were associated with increased RTs as well. Thus, decreased performance levels were observed for trials characterized by aberrant measures of gaze control behavior. These findings are critical to the development of valid and reliable real-time monitoring systems and provide a compelling argument for including TT saccade metrics in oculomotor-based alertness assessment batteries whenever such measures are available.

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REFERENCES

[1]A.G. Bills, "Fatigue in Mental Work", *Physiology Review*, **17**, 436-453, 1937.

[2]E.J. Sirevaag, J.W. Rohrbaugh, J.A. Stern, A.B. Vedeniapin, K.D. Packingham, C.M. LaJonchere, "Multi-dimensional Characterizations of Operator State: A Validation of Oculomotor Metrics", *U.S. Dept. of Transportation Report*, **DOT/FAA/AM-99/28**, 1999.

[3]W.W. Wierwille, L.A. Ellsworth, S.S. Wreggit, Fairbanks, C.L. Kirn, "Research on vehicle-based driver status/performance monitoring: development, validation, and refinement of algorithms for detection of driver drowsiness", *National Highway Traffic Safety Administration Final Report*, **DOT HS 808 247**, 1994.

[4]D.F. Dinges, J.W. Powell, "Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations", *Behavioral Research Methods Instrumentation and Computers*, **17**, 625-655, 1985.

[5]P.J. Oster, J.A. Stern, "Measurement of Eye Movements. Electrooculography", *Techniques in Psychophysiology*, J. Martin, P.H. Venables, Wiley, New York, 1980.

[6]G. Keppel, *Design and Analysis: A Researcher's Handbook*, 169-170, Prentice Hall, New Jersey, 1991.

*ejsireva@artsci.wustl.edu; phone 1 314 286-1371; fax 1 314 454-0432